Geological Survey of Canada
Commission géologique du Canada

PAPER 85-15

SEDIMENTOLOGY OF THE GOLDENVILLE FORMATION, EASTERN SHORE, NOVA SCOTIA

JOHN W.F. WALDRON
LYNDON R. JENSEN

Canada

1985

86-0344/

Nova Scotia

Department of Mines and Energy

CONTRIBUTION TO CANADA-NOVA SCOTIA
CO-OPERATIVE MINERAL PROGRAM 1981-84

The senior author was on contract to the Geological Survey of Canada. Field operations, field support staff, chemical analyses and publication production were funded by Canada. Office and ancillary services were provided by Nova Scotia Department of Mines and Energy.

Energy, Mines and Resources Canada
Énergie, Mines et Ressources Canada
Geological Survey of Canada
Commission géologique du Canada

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Available in Canada through

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or by mail from

Canadian Government Publishing Centre
Supply and Services Canada
Ottawa, Ontario, Canada K1A 0S9

and from

Geological Survey of Canada
601 Booth Street
Ottawa, Canada K1A 0E8

A deposit copy of this publication is also available
for reference in public libraries across Canada

Cat. No. M44-84/18E Canada: $5.00
ISBN 0-660-11706-1 Other countries: $6.00

Price subject to change without notice

Authors Addresses

John W.F. Waldron
Department of Geology
St. Mary's University
Halifax, Nova Scotia
B3H 3C3

Lyndon R. Jensen
R.R. 3
Middleton
Annapolis County
Nova Scotia
B0S 1P0

Critical Readers
F.W. Chandler
J.R. Henderson

Original manuscript received 1984-03-31
Final version approved for publication 1984-10-22

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SEDIMENTOLOGY OF THE GOLDENVILLE FORMATION, EASTERN SHORE, NOVA SCOTIA

Abstract

The Goldenville Formation is a thick sequence of metamorphosed interbedded sandstone and slate of Cambro-Ordovician age, which underlies much of southern mainland Nova Scotia. Magnetic anomalies associated with particular horizons within the formation were traced along strike using a vertical gradient magnetometer for up to about 15 km. Stratigraphic sections were measured through laterally equivalent parts of the formation. Paleocurrent measurements based on flutes and grooves were reoriented using estimates of tectonic strains obtained by measuring sand-volcanoes.

The Goldenville Formation sediments have been classified into the following sedimentary facies: graded sandstone; laminated to massive sandstone; internally scoured sandstone; muddy sandstone; intraclast conglomerate; cross-stratified sandstone; crosslaminated slate; and laminated slate. Sedimentary structures indicate that most sandstones were deposited by high-and low-concentration turbidity currents that flowed generally from west to east but which show considerable variation in current direction, consistent with deposition on a submarine fan. Grain flow and fluidized flow occurred during deposition from high-concentration turbidity currents but were less important than turbidity currents in sediment transport. Muddy sandstones were formed by remobilization of sand and mud in debris-flows on slopes. Intraclast conglomerates were deposited by high-energy flows that eroded large amounts of underlying sediment. Rare cross-stratified sandstones were deposited by bottom-currents with variable direction. Slates interbedded with the sandstones probably represent a mixture of hemipelagic mud and deposits from dilute turbidity currents; some may have been reworked by bottom-currents.

Comparison of laterally equivalent sections shows that major lateral facies changes are present; sandstone-dominated packages from 5 to 150 m thick disappear when traced laterally over distances of several kilometres. The thicker sandstone packages represent submarine-fan channel complexes flanked by raised levees; currents on the levees diverged from those in the channel axis. Channels reached depths of at least 40m and probable widths of 2 to 3 km. Thinner packages were deposited in less persistent, shallow channels that probably lacked levees, and possibly also in small depositional lobes. Slate-dominated intervals represent inter-channel deposits.

Résumé

La formation de Goldenville est une épaisse séquence de grès et de schiste ardoisier interstratifiés et métamorphisés d'âge Cambrien-Ordovicien qui est sous-jacente à une grande partie de la section sud de la Nouvelle-Écosse. Au moyen d'un magnétomètre à gradient vertical, des anomalies magnétiques associées à certains horizons dans la formation ont été suivies parallèlement à la direction sur une distance d'environ 15 km. Des coupes stratigraphiques ont été mesurées dans les parties latéralement équivalentes de la formation. Les paléocourants, mesurés à partir de rainures et de cannelures, ont été réorientés en se fondant sur les estimations de la déformation tectonique obtenues en mesurant les injections de sable.

Les sédiments de la formation de Goldenville sont classés en divers faciès sédimentaires: grès bien classé; grès feuilleté à massif; grès à affouillement interne; grès boueux; conglomérat à intraclastes; grès à stratification oblique; schiste ardoisier feuilleté obliquement schiste ardoisier feuilleté. Les structures sédimentaires révèlent que la plupart des grès ont été déposés par des courants de turbidité à concentrations forte et faible qui coulaient habituellement de l'ouest à l'est; toutefois, la direction des courants était très variable, ce qui laisse croire que la sédimentation a eu lieu sur un delta de canyon sous-marin. Il y a eu écoulement des grains et écoulement fluide lors de l'accumulation des sédiments transportés par les courants de turbidité à forte concentration; cependant, ces types d'écoulement ont été moins importants que les courants de turibité pour le transport des sédiments. Les grès boueux ont été formés par remobilisation du sable et de la boue dans des coulées de débris sur les pentes. Les conglomérats à intraclastes ont été déposés par des coulées à forte énergie qui ont arraché d'importantes quantités de sédiments sous-jacents. Les rares grès à stratification oblique ont été déposés par des courants de fond à direction variable. Les grès et schistes ardoisiers interstratifiés représentent vraisemblablement un mélange de boue hémipélagique et de dépôts transportés par des courants de turbidité dilués; certains d'entre eux ont peut-être été remaniés par des courants de fond.

Une comparaison des sections latéralement équivalentes révèle l'existence d'importants changements latéraux de faciès; les intervalles riches en grès, dont l'épaisseur varie de 5 à 150 m, disparaissent latéralement sur une distance de plusieurs kilomètres. Les intervalles plus épais de grès représentent des complexes de chenaux de delta de canyon sous-marin qui étaient bordés de levées naturelles; les courants sur les levées ont divergé des courants dans les chenaux. La profondeur des chenaux a vraisemblablement atteint au moins 40 m et leur largeur, 2 ou 3 km. Les intervalles moins épais ont été déposés dans des chenaux éphémères peu profonds, vraisemblablement dépourvus de levées naturelles, et peut-être aussi dans de petits lobes de sédimentation. Les intervalles riches en schistes ardoisiers représentent des dépôts accumulés entre les chenaux.

INTRODUCTION

Regional setting

The Meguma Group, a thick sequence of metamorphosed lower Paleozoic clastic sedimentary rocks, underlies much of southern mainland Nova Scotia (Fig. 1). This area constitutes the Meguma Zone (Williams, 1978) or Terrane of the Appalachians, but has no known equivalents elsewhere in the Appalachian belt. Possible equivalents of the Meguma sediments are however found in North Africa (Schenk, 1971) in an area that lay adjacent to Nova Scotia before the opening of the Atlantic.

The Meguma Group is divided into two formations. The Goldenville Formation, the lower of these, consists of a great thickness (at least 5600m) of grey metamorphosed sandstone interbedded with greenish slates. It is overlain by the Halifax Formation, which is everywhere finer grained, consisting mainly of slate. Regional metamorphism in the Meguma Group varies from low greenschist facies, to upper amphibolite facies in the extreme southwest and east. Contact metamorphic effects of Devonian granitoid plutons (Fig. 1) are generally superimposed on the regional metamorphism.

There is little direct evidence of the age of the Goldenville Formation. Poorly preserved graptolites indicating an Arenig (Early Ordovician) age are recorded by Schenk (1970) and Poole (1971). Trace fossils indicate an Ordovician or younger age according to Pickerill and Keppie (1981). Muscovite potassium-argon dates of 476 ± 19 and 496 ± 20Ma are interpreted by Poole (1971) as indicating the age of deposition or diagenesis.

Indirect evidence for the age of the Goldenville Formation comes from Early Ordovician graptolites in the overlying Halifax Formation (Smitheringale, 1960; Crosby, 1962). Detrital zircons in the Goldenville Formation yielded ages close to 600Ma, providing an upper age-limit (T.E. Krogh, personal communication, 1984).

Previous sedimentary studies

The Goldenville Formation was named by Woodman (1904a) who interpreted it as a product of a turbulent, shallow-marine environment, and remarked (1904b) upon large-scale lateral discontinuity of the sandstone layers. Phinney (1961) was the first to propose a turbidite origin for the sandstones. Subsequently Campbell (1966) identified a predominant northeastward paleocurrent direction, and postulated deposition in a deep sea trough. Schenk (1970) systematically studied the entire Meguma Group using a grid-sampling system, and proposed that turbidity current deposits had been extensively reworked by contour-following bottom currents. Harris (1971; 1975) studied the Taylor Head area in detail, and postulated deposition mainly by turbidity currents. Schenk (1973) compared the Meguma sediments with abyssal plain deposits of the western North Atlantic, whereas Harris and Schenk (1975) applied a submarine fan model, postulating deposition in the mid-fan region.

General characteristics of the sediments

We have carried out a detailed field study of Goldenville sediments in the coastal area southwest of Sheet Harbour (Fig. 1). Many of our conclusions are based on lateral correlation in this area of stratigraphic horizons identified by magnetic gradiometer (discussed below). Additional sections were measured at Owl Head, Coomb Cove, Crooks Island, Redman Head, Mitchell Bay, and Indian Harbour (Fig. 1).

The petrography of the Goldenville sandstones was studied by Harris (1971); our limited investigations confirm his main conclusions. Metamorphic recrystallization has obliterated many details of the original petrography. The sand-size component of most samples includes mono-and polycrystalline quartz, alkali and plagioclase feldspars, muscovite, epidote group minerals, tourmaline, zircon, and opaques. Sand-size aggregates of chlorite may represent original rock fragments. Medium- to fine-grained sand grains are typically angular or subangular and poorly sorted, but some samples show a component of coarse to very coarse, well-rounded (Fig. 2) "millet-seed" sand; these generally have a strikingly bimodal grain-size distribution. The abundant fine-grained matrix of the sandstones has entirely recrystallized to metamorphic chlorite and epidote; its original mineralogy and grain size are unknown.

Slates are also thoroughly recrystallized; quartz, sericite and chlorite are discernable petrographically, with local growth of post-tectonic biotite porphyroblasts.

The petrology of the Goldenville sandstones suggests a continental source, with a variety of source lithologies. The origin of the coarse, well rounded sand component is unknown; it may reflect either a contemporary environment of repeated reworking in the source area or derivation of material from an older supermature sandstone.

Sandstone and slate are repetitively interbedded throughout the Goldenville Formation. Bed thicknesses range from 1 cm to several metres, although some units composed entirely of sandstone beds ("amalgamated" beds) are up to 150m thick. Most beds are laterally continuous on the scale of single outcrops, but our lateral correlation has shown that major facies changes occur in some parts of the sequence when beds are traced for greater distances (100m-5km) along strike.

Our sedimentological work is based on measured stratigraphic sections with a total thickness of about 8km. The thicknesses of all beds more than 5cm thick were recorded. In these sections only gross lithology (sandstone, slate or intermixed) was recorded, together with the occurrence of sedimentary structures. Figures 4 to 7 show these sections in a simplified format, together with those of Harris (1971) which were redrawn in the same format but not remeasured. Only beds thicker than 1m are distinguished on Figures 4 to 7; thinner-bedded intervals containing both sandstone and slate are shown without ornament on the columns.

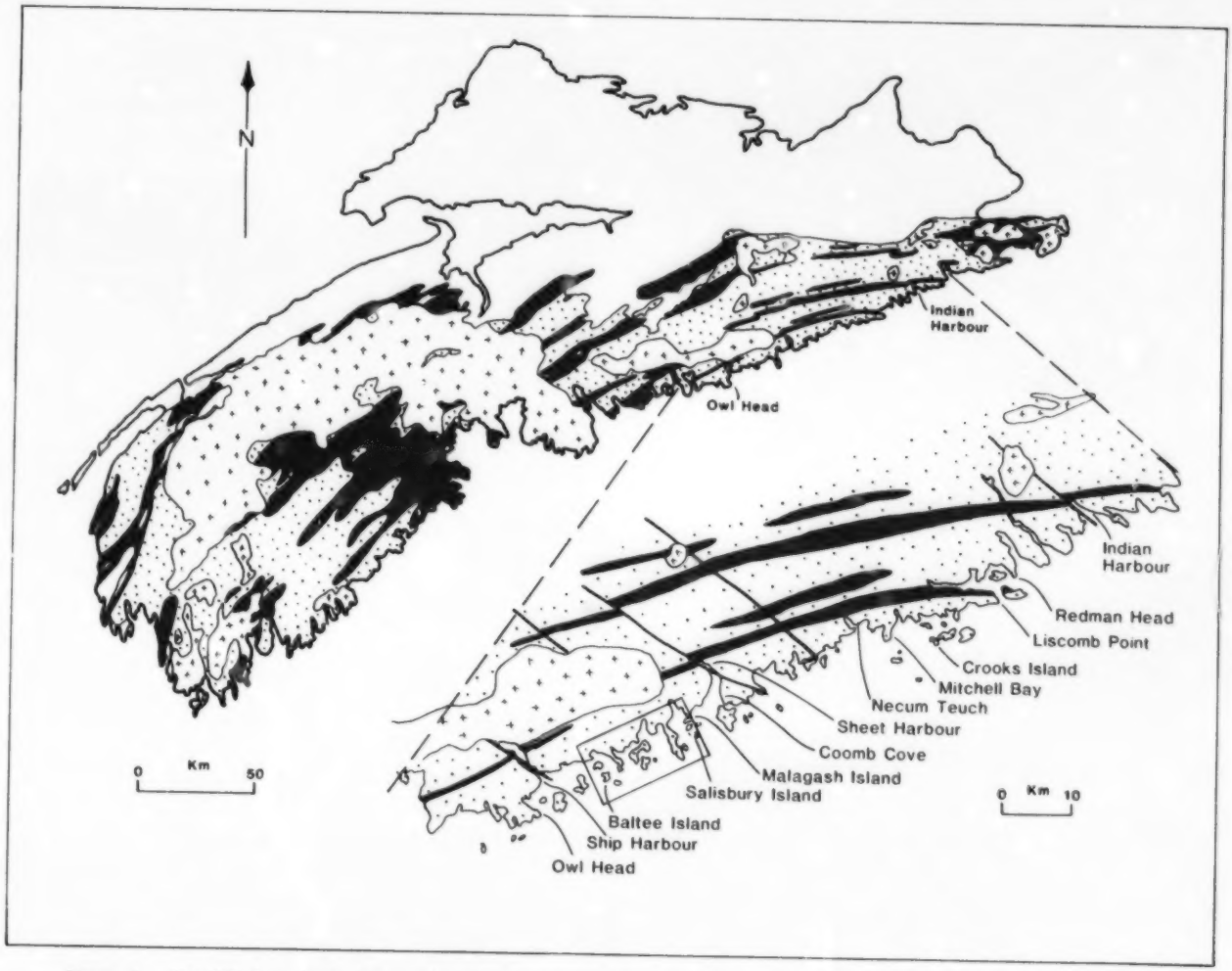


Figure 1. Simplified geological map of southern mainland Nova Scotia showing localities mentioned in text. Stipple: Goldenville Formation; black: Halifax Formation; crosses: intrusive rocks. Box encloses area densely covered by vertical gradient magnetometer traverses, shown in Figure 3.

These "general" measured sections were supplemented with more detailed work on well-exposed and well-correlated portions of the sequence, in which estimated grain size was recorded, together with descriptions of all the sedimentary structures and their distribution within beds. Detailed measured sections are shown in Figures 8 to 9.

Structure

The Meguma Group was folded during the Acadian Orogeny into an arcuate pattern of upright megascopic folds trending between north-south in the extreme southwest to almost east-west at the eastern extremity of mainland Nova Scotia. A strong cleavage is everywhere developed; cleavage is penetrative in slate but generally is a spaced pressure-solution cleavage in the sandstone (Henderson, 1983; O'Brien 1983). Other deformational fabrics have been identified in the Meguma Group, both earlier and later than the main folding (O'Brien, 1983), but these are only sporadically developed in the areas studied by us.

A variety of veins, some of which are gold bearing, are seen in the Goldenville Formation; because of their economic interest these have been the subject of a number of detailed studies (Henderson, 1983; Haynes, 1983). Most veins in the areas studied by us crosscut bedding and show only a small component of movement parallel to the vein walls. Some are perfectly bed-parallel however; these typically show lineations either parallel or steeply inclined to the vein walls and contain flakes of slate. Some authors (Haynes, 1983) have interpreted these as synsedimentary exhalative deposits; however, the veins observed by us were sharply bounded and showed no sign of mixing with sediment on the scale of individual grains. They consist of megaquartz with textures unlike those of siliceous sediments, and show no sign of sedimentary re-working. They are believed to represent fractures and shear surfaces that developed early in the tectonic history of the rock (Graves and Zentilli, 1982; Henderson, 1983). These veins must be taken into account in sedimentary analysis because considerable displacement may have occurred along them. Fortunately, they are rare in the areas studied by us, and do not occur in any of the sections selected for detailed study.

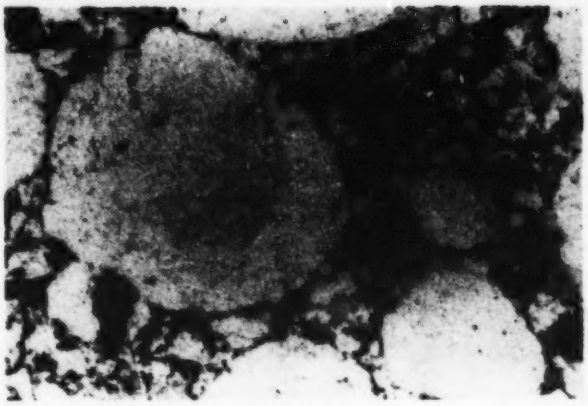


Figure 2. Photomicrograph of Goldenville sandstone showing 'millet-seed' grains in a finer, immature matrix. Field of view 3mm approx.

High-angle faults trending approximately 120° occur throughout the eastern Meguma Group. A number occur in the area of detailed study (Fig. 3) where they offset the stratigraphic units and the axial trace of the Sober Island Syncline. Several can be located from air photographs; the existence of others is inferred from the distribution of stratigraphic units.

GEOPHYSICAL WORK

Stratigraphic and sedimentological studies in the Goldenville Formation have been hampered by the lack of marker horizons or distinct lithological units in the thick sequence of metamorphosed sandstones and slates. Stern and Henderson (1983) carried out a magnetic survey at ground level of a part of the formation and were able to show that magnetic anomalies were associated with particular horizons. Both total-field and vertical gradient data were used by them, but the vertical gradient data provided better resolution of individual anomalies. We have adapted this method in the systematic surveying of well-exposed coastal sections and have used this method to subdivide and correlate stratigraphic sections within the Goldenville Formation. This correlation has enabled us to trace individual sandstone beds and packages of beds up to 15 km along strike, providing a basis for improved sedimentological interpretation.

Methods

Location of lines

Because correlation was to be used as a basis for detailed sedimentological work, magnetometer traverse lines were laid out mainly in areas of reasonably good exposure, principally along shorelines. The area between Baltee and Salisbury islands, Halifax County (Fig. 1) was found to be particulary favorable for this study, as it provides many well-exposed coastal sections through the same beds. Much of the work was concentrated here. Additional, more widely spaced lines were selected to the west at Owl Head, to the north of Sober Island Syncline at Popes Head, Malagash Island, and Coomb Cove, and farther to the east at Mitchell Bay and Liscomb Point (Fig. 1.). In selecting study areas, it was found that well-exposed rocky coastlines were relatively rare in areas of southerly dip, posibly due to the plucking action of south-flowing ice during glaciation.

Surveying of lines

Lines were surveyed using a Brunton compass and survey tape, with stations marked at intervals of 20m or less. Usually, traverse lines were oriented perpendicular to the strike of bedding, and strike-parallel offsets were used to accommodate irregularities in the coastline wherever possible. In some cases, lines oblique to strike were used; this was done when a perependicular route would have necessitated extremely frequent offsets, or when the strike could not be determined because of local lack of exposure.

An EDA Instruments PPM-500 vertical gradient magnetometer was used to measure total magnetic field and vertical gradient at 2m intervals along the survey lines. The instrument consisted of two proton magnetometer sensors mounted vertically 1m apart in a single pole. At each recording position, the total field value at the lower sensor, and the difference between total field values at the two sensors, were recorded in the machine's memory; the second of these values approximates the vertical gradient of the total field 3m above ground level. Location numbers and distance along the traverse line were also recorded in the memory. Notebook records were kept of the corresponding survey station numbers, to permit correct positioning of magnetic profiles on the map (Fig. 3).

A base station magnetometer, also supplied by EDA Instruments, was run at the base camp at Necum Teuch (Fig. 1) to allow correction of small diurnal magnetic variations, but some base station data were lost due to incorrect connection of the instrument preventing correction. However, vertical gradient profiles were found to provide superior resolution of anomalies. An additional advantage of vertical gradient data is that it does not suffer from significant diurnal variation, and does not therefore require correction.

Plotting of the data

The Programm MAGEDA, supplied by EDA Instruments, was modified by us to facilitate plotting of magnetic profiles. Profiles were prepared as follows:

1. Plots of total field and vertical gradient at a scale of 1:10 000 were prepared for mounting directly on orthophotomaps. Parts of survey lines which were oblique to strike were projected onto a strike-perpendicular line by adjusting the scale of the plot to:

   $$1{:}10\,000 \sec \phi$$

   where ϕ is the angle between the traverse line and the strike. These profiles are shown in reduced form in Figure 3.

2. Profiles showing vertical gradient were plotted against stratigraphic elevation at a scale of 1:5000 and 1:500. To convert distance to stratigraphic elevation, a correction for dip was applied:

   $$\text{scale} = 1{:}5000\ (\sec \phi)\ (\sec \theta)$$
   $$\text{or scale} = 1{:}500\ \ (\sec \phi)\ (\sec \theta)$$

   where θ is the dip.

Measurements of dip were taken at intervals to facilitate this correction; because these dip measurements were not precisely representative of the average dip of the section, and also because of topographic effects and the inherent inaccuracy of bed-by-bed section-measuring procedures, there is usually a residual mismatch between graphic logs of the measured sections and the corrected gradiometer profiles. Tie-in points at 20m intervals were therefore recorded wherever possible to allow precise matching of magnetic features with the beds over which they occurred.

Results

Characteristics of profiles

Figures 4 to 7 show vertical gradient profiles adjacent to stratigraphic logs of the equivalent sections. Large positive gradients are clearly associated with packages of thickly bedded sandstones, although not all sandstone packages are associated with peaks. Sandstone samples show susceptibility values in the range 5 to 18 $\times 10^{-4}$ cgs susceptibility units; contrasts of this order between adjacent packages a few metres thick would account for the magnitude of the peaks observed.

Stern and Henderson (1983) determined the susceptibility of similar sandstones in the Crooks Island area (Fig. 1) to be due to magnetite particles. Examination of polished thin sections suggests that magnetite is responsible for the susceptibility of our samples also although results of quantitative analysis of the magnetic mineralogy are not yet available.

No attempt was made to model the shape of individual peaks. Because the gradiometer is close to ground level, the vertical gradients recorded are strongly modified by local topography. Effects of topography were noticed by the instrument operators. For example, massive sandstones often form topographic eminences and low cliffs; when these sandstones were associated with high positive gradients, large negative values were generally recorded in adjacent topographic lows, whereas large negative gradients were rare on level ground. Wherever possible, we chose a topographically smooth route for traverse lines. However, the profiles must be regarded as a function both of magnetic susceptibility of the sandstone and of local topography, which is itself largely controlled by lithology.

The amplitude of vertical gradient anomalies falls rapidly with distance from source; thus, profiles over thick overburden are relatively flat. Nevertheless, the vertical gradient data still provide superior resolution when compared with total field profiles, and can be correlated satisfactorily if the overburden has fairly even thickness. (For example: compare laterally equivalent profiles on Gerard and Phoenix islands in Figure 3.)

Correlation

Comparison of laterally equivalent vertical gradient profiles (Fig. 3) indicates that patterns of anomalies show continuity along strike over distances of several kilometres. The stratigraphic sequence on the south limb of the Sober Island Syncline has been divided into stratigraphic units on the basis of distinctive motifs in the gradient profiles. Two types of magnetic features form the boundaries between units:

1. Boundaries between magnetically "quiet" areas (usually with a low negative gradient) and "noisy" areas characterized by multiple, closely spaced peaks.
2. Single isolated peaks in the middle of quiet intervals.

Following identification of the magnetic units shown in Figure 3, comparison of laterally equivalent measured sections in some cases allowed recognition of laterally continuous lithological units. More detailed correlation was therefore carried out using stratigraphic sections mounted alongside the vertical gradient profiles as shown in Figures 4 to 7.

Magnetically quiet regions and clusters of peaks show lateral continuity over distances as great as the 15km along strike shown in Figure 3. Individual peaks, on the other hand, may die out when traced laterally. Such peaks usually correspond to laterally discontinuous sandstone packages. Where the stratigraphically highest or lowest peak in a cluster dies out in this way, the boundary of the cluster becomes slightly diachronous. This phenomenon is most clearly shown at the top of a conspicuous interval of negative gradients identified as unit I. This interval appears to thicken westwards as a result of the disappearance of basal peaks corresponding to unit J (Fig. 6).

Summary of stratigraphic sequence

The package exposed on the south limb of the Sober Island Syncline in the area of Figure 3 is about 2.5km in present-day stratigraphic thickness. The package may have been thickened tectonically. The lowest part (Fig. 4) comprises magnetic unit A, and is exposed only on the eastern shore of Taylor Head, where it was measured by Harris (1971). Units B and C are exposed on Tangier Island and intermittently on Taylor Head. Only tentative correlation could be achieved between these two widely separated sections. Higher parts of the sequence are exposed in multiple sections on the coasts of several islands, permitting detailed correlation. Unit D is a magnetically quiet interval characterized by negative vertical gradients with a central positive peak. It is overlain by a laterally persistent cluster of peaks identified as Unit E (Fig. 5). This unit corresponds to a major localized sandstone-dominated package interpreted as the fill of a submarine channel complex (see below). Units F and G are magnetically quiet regions separated by a single peak, forming a distinctive and easily correlated pattern recognizable in many profiles. Unit H is a thick interval which is difficult to subdivide on the basis of magnetic features alone. However, a number of peaks are associated with thin (10-20m) sandstone packages that are relatively laterally continuous, and allow finer subdivision (Fig. 4 and 6). Harris (1971) achieved a lateral correlation from Taylor Head to Phoenix Island in part of this interval. Unit I (Fig. 6) is a magnetically quiet unit of negative gradients that extends from Salisbury Island in the east as far west as Phoenix Island. The corresponding stratigraphic sequence is thinly bedded and slate-rich. The unit would be expected to appear on Ironbound Island, but instead a thick mass of sandstones is associated with numerous peaks in the gradient profile. These sandstones are believed to be the fill of channel complex cut into unit I, accounting for its disappearance. Unit J is a thick interval of numerous peaks which except at its base is only intermittently exposed to the west of Taylor Head, and which can be subdivided only with difficulty. The overlying units K to O are characterized by alternating peak-clusters and quiet intevals (Fig. 7). These units are well exposed on the coasts of Gerard Island and Popes Head, but are partly covered by overburden on Taylor Head. The stratigraphically highest units P and Q occur in the core of the Sober Island Syncline, where they can be identified with confidence on both sides of the axial trace. To the north, the south dipping sequence equivalent to units A to O is less well exposed than on the south limb. Provisional correlation of the sequences on Popes Head and Malagash Island is shown in Figure 3. The profile on Taylor Head has low amplitude north of the fold axial surface an is affected by spurious peaks due to metal stream culverts, etc. A profile to the east, at Coomb Cove (Fig. 1) also on the north limb, correlates well with that on Malagash Island.

PALEOCURRENT DATA

Current indicators in the Goldenville sandstones include grooves and other tool marks on the bases of beds, flutes and flute-like scours within beds, cross-stratification, and ripple crosslamination at the tops of beds. Siltstones frequently also show ripple crosslamination but because of the strong cleavage it is not usually possible to obtain more than a rough impression of current direction.

The most abundant and accurately measurable current indicators are grooves on the base of beds. These provide "axial" paleocurrent data, showing only the direction but not the sense of flow. Flutes on the bases of beds generally provided unambiguous "directional" data, but with less accuracy than the more elongated grooves. The inaccuracy was more marked in the case of the more widely flared structures here termed "scoop" structures—flute-like scours within sandstone beds. The symmetry of these structures was modified by tectonic strains, with the result that few satisfactory measurements could be obtained.

A number of beds displayed ripples on their top surfaces. These were only measurable when straight-crested, and when a large area of bedding surface was exposed. An unambiguous current direction could only be obtained when ripples were visible in cross-section; otherwise the lee and stoss sides could not be distinguished owing to the distortion of the ripples by tectonic strains. Linguoid ripples were frequently seen but could not be used to provide current directions because their symmetry was destroyed by strain. Thus most of the paleocurrents measured were from grooves. Figure 10a shows the distribution of "axial" current directions (flutes and grooves) measured from units C to E, after rotation to horizontal about the local strike. Figure 10b shows the smaller number of directional data (flutes only), and indicates that the eastward mode in Figure 10a represents the true current direction. Crosslamination and scours exposed only in cross-section on cleavage and joint surfaces showed an almost universal eastward component of current flow, confirming this conclusion and that of most previous workers that the mean paleocurrent direction was eastward.

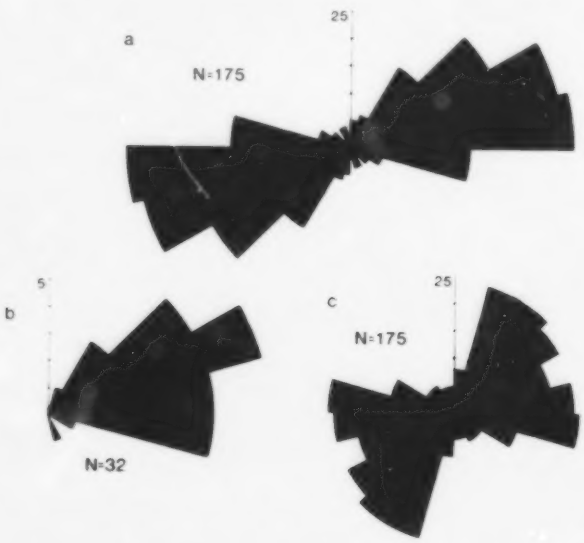


Figure 10 Paleocurrent rose diagrams.
(a) Units C (top), D and E; all data.
(b) Same, directional data (mainly flutes) only.
(c) All data, after removal of estimated strain.

Effects of strain

Tectonic strains may have affected the measured current directions in several ways:

1. Distortion of an individual bedding surface has caused relative rotation of lines on that surface.
2. If a rotational component of strain other than simple rotation about the local strike is present then an additional rotation will have been imposed on all lines.
3. If strain is inhomogeneous on a scale larger than that of individual paleocurrent markers, then similarly oriented lines on different bedding surfaces may have suffered different rotations.

We have used sand volcanoes to obtain estimates of the strain ratio in the plane of bedding in order to remove the effects of distortion from the *relative* orientation of paleocurrents (effect 1). The absolute original orientation of these currents is not known, because the rotational component of strain (2) cannot be determined. We have removed the effects of tilting by rotation to horizontal about the strike. Because strain markers are only available on a small proportion of bedding surfaces, and because these are not generally the same surfaces as those from which paleocurrents are measured, it is difficult to make a rigorous assessment of the effect of inhomogeneities in the strain (effect 3, above). However, because the only folds are relatively angular and extremely large compared with the thickness of individual sandstone and slate layers, it is likely that the strains developed in bedding surfaces are fairly homogeneous on fold limbs. Proposed strain models (Keppie, 1976; Henderson, 1983) involve flexural slip or flexural flow of slate combined with predominantly tangential strain in sandstone, plus a superimposed component of homogeneous strain. The effects of tangential strain on bedding surfaces would be small, due to the large radius of curvature of fold hinges compared with the thickness of individual sandstone beds. If superimposed homogeneous strain occurred *before* folding, as suggested by Henderson (1983), then its effect on bedding surfaces would be constant. Homogeneous strains developed *after* folding would lead to a dip-dependent strain ratio on bedding surfaces. Most current directions were measured on surfaces dipping between 40° and 50° to the north; a reasonably constant strain ratio would therefore be expected. However, inhomogeneities on a scale smaller than that of individual grooves and flutes may affect the accuracy of strain determinations; their effect is discussed below.

If oblique flexural slip occurred during folding, then all currents on south-dipping fold limbs would be rotated relative to those on north limbs. The paleocurrent data discussed here are entirely from the north-dipping limb of the Sober Island Syncline.

Estimation of the strain-ratio

Previous workers (e.g. Harris, 1971) have estimated the strain ratio in the plane of bedding from the aspect ratio of deformed sand volcanoes. This method is based on a number of assumptions:

1. The sand volcanoes were initially circular. This might not be true if bottom currents operated during sand volcano formation. However, where a vent is visible, it is usually in the centre of the volcano, suggesting that the volcanoes were probably originally symmetrical.
2. The sand volcanoes deformed homogeneously with their matrix. Since the volcanoes are usually coarser grained than surrounding material, this assumption may not be valid. Bedding-cleavage

intersection lineation often diverges around sand volcanoes, suggesting that they underestimate the true strain ratio. They may also have undergone relative rotation during deformation.

Aspect ratios of sand volcanoes are difficult to measure accurately when volcanoes have diffuse edges. We measured sharply bounded sand volcanoes from two bedding surfaces on Taylor Head, which yielded average strain ratios of 1.96 and 1.92. These figures are slightly higher than that used by Harris (1971). In all cases, the long axis of the sand volcanoes was almost parallel to strike, pitching between 0 and 15° to the west, approximately parallel to both the bedding/cleavage intersection lineation and the regional fold axis. (The plunge of the latter varies from gently westwards to gently eastwards across the area.)

Because of the uncertainties and assumptions involved in this method, a second method of strain determination, based on different assumptions, was attempted. Distances between adjacent sand volcanoes were measured for a large number of volcanoes on a single surface (Fig. 11). The pitch of the line joining each pair of volcanoes was measured also. Randomly distributed objects would show no dependence of distance on direction, whereas on a deformed surface, initially random markers would show greater separation in directions close to the long axis of the strain ellipse as shown in Figure 11. This method is described by Ramsay (1967) for sutured sedimentary grains, but is equally applicable to sand volcanoes when these have a reasonably uniform size on a particular bed.

The major assumption inherent in this method is that the sand volcanoes were initially distributed independently of direction. This may not have been true if, for example, sand volcanoes were located preferentially above sheet-like dewatering structures. The results obtained from beds exposed on Taylor Head do not tightly constrain the strain ratio, but are consistent with the strain ratios in the range 1.9-2.0 obtained from the same beds by the first method. Visual curve-fitting indicated that they would also be consistent with somewhat higher ratios about 2.5, but no higher. A "best estimate" of 2.0 was used in unstraining the paleocurrent measurement discussed in the following sections. The precise value is not critical, however, to any of the major conclusions based on paleocurrent data; closely similar, though slightly more dispersed paleocurrent patterns result if a strain ratio of 2.5, is assumed, for example.

It has occasionaly been suggested that the strong clustering of observed paleocurrent structures in the Goldenville Formation is *purely* the result of strain. Strain ratios above 5 are required to account for the present clustering of most datasets by tectonism alone. The good preservation and only moderately distorted appearance of a variety of sedimentary structures indicate that this value is unreasonably high. The conclusion, that the clustering of paleocurrents was primary, is confirmed by the substantial differences in modal direction in different parts of the same sequence (Fig. 12).

Presentation of results

Current directions were reoriented relative to the strain axes and then rotated about strike to horizontal, yielding an original azimuth relative to present-day North. Because of the possibility of large-scale rotation of the Meguma Group, this cannot be interpreted as an original direction. Current directions are shown in two ways in graphic logs (Fig. 8, 9). To the left, the originally measured pitch, either to the west or east, is displayed. This method of presentation is most useful when adjacent along-strike sections are compared; a horizontal arrow indicates that one section represents a point directly down-current from the other. To the right is shown the azimuth of the current relative to present-day North after removal of estimated strain and rotation to horizontal. In this format, a vertical arrow represents a north-south current.

SEDIMENTARY FACIES

Despite their initially uniform appearance, the sediments of the Goldenville Formation reveal major variations when viewed on a scale of kilometres. Vertical sequences (Fig. 4 to 9) show major variations in their percentage of sandstone and in sedimentary facies. Distinct sandstone-dominated packages ranging from 5m to 150m in thickness are present in all the sections measured. Correlation by gradiometer reveals that the majority of these packages are discontinuous when traced along strike over distances of 5km or more. Most of these packages are interpreted by us as submarine channel fills; however some may represent depositional lobes. In this section we review the characteristics of individual sandstone and shale beds and packages; large-scale features of the depositional system are reviewed in a later section.

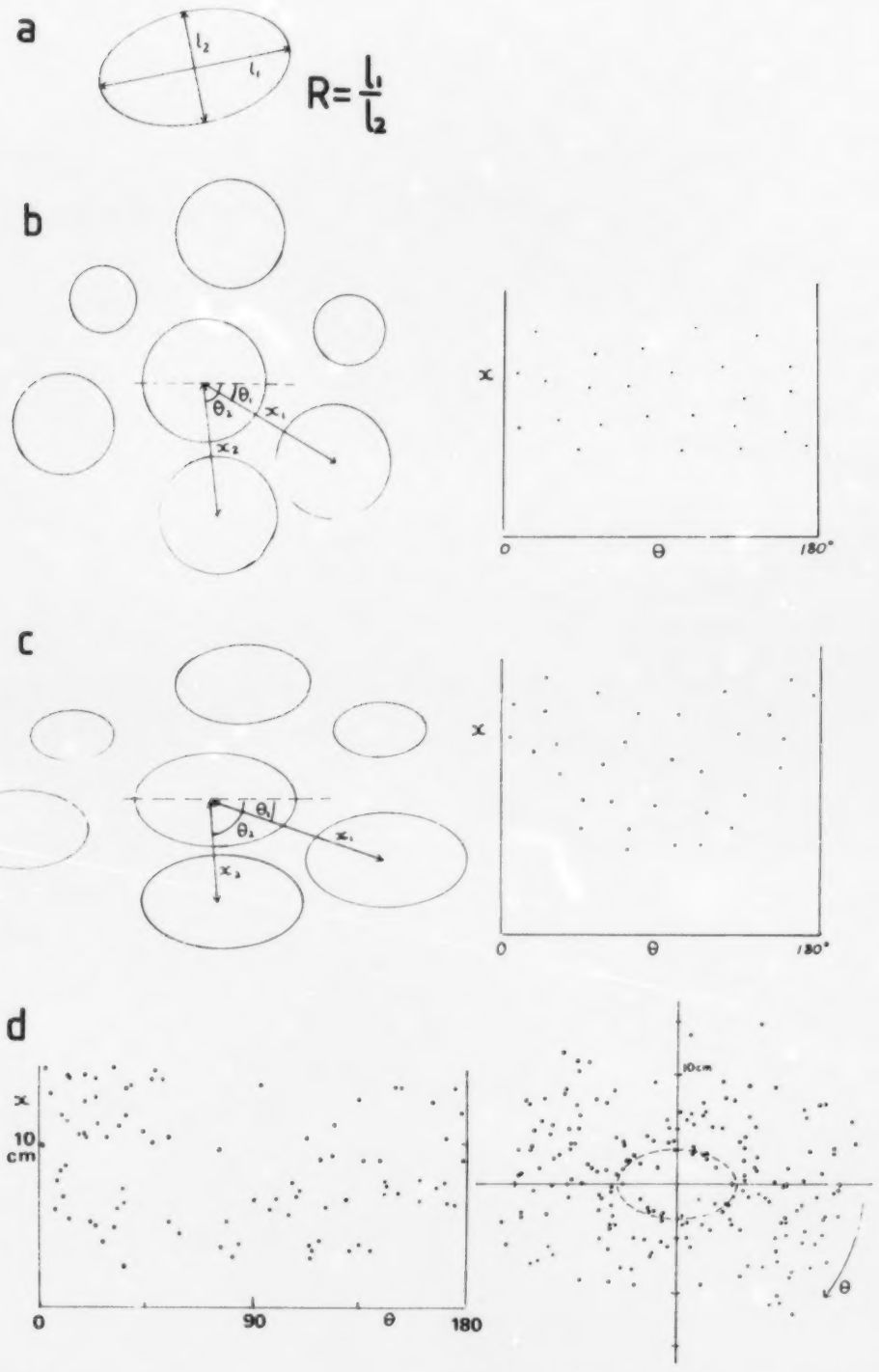
Previous workers (Phinney, 1961; Harris, 1971; Harris and Schenk, 1975) have interpreted the Goldenville Formation sandstones as turbidites. However, only a small proportion of the beds (graded sandstones; see below) show Bouma (1962) sequences, considered typical of "classical turbidites". For this reason Harris and Schenk (1975) proposed that some sandstone layers may have been transported by processes of grain flow and fluidized flow. The roles of these processes are discussed at the end of this section.

For convenience of discussion, we have classified the sediments into eight sedimentary facies, characterized by different combinations of sedimentary structures, thickness and grain-size characteristics. Most of these facies represent arbitrary subdivisions in a continuum of types. The major distinguishing features of each facies are listed in Table 1; each facies is described in greater detail below.

The sandstone and slate facies display a great variety of sedimentary structures which provide evidence of their mode of deposition; the origins of sedimentary structures and other sedimentary features of single beds are discussed when each is first described. More general interpretations are left until later sections.

Graded sandstone

Graded sandstones occur predominately in slate-rich parts of the Goldenville Formation. They consist generally of medium to very fine sandstone which grades continuously up into silt and then into fine slate (Fig. 13). These sandstones generally show parallel laminations passing up into climbing ripple crosslaminations. A basal massive portion is sometimes present, and may contain slate intraclasts; these appear lithologically similar to underlying slate beds. Convolute lamination occurs rarely in the upper parts of these beds, and dish structures have also been recorded. Basal surfaces often show load casts, groove casts, or more rarely, flute casts indicating eastward paleocurrents. The sequence of sedimentary structures shown by these beds can be accommodated within the Bouma (1962) sequence of sedimentary structures, characteristic of "classical" turbidites. The majority of beds seen by us would be characterized as Bouma Tabc(d)e or Tab(d)e units, and correspond to submarine-fan facies C of Mutti and Ricci-Lucchi (1972). Sandstone beds with the ripple-laminated c division at the base are rare; most crosslaminated graded beds consist entirely of cleaved siltstone (see below: crosslaminated slate). Several variations on this typical sequence have been recorded. Well graded beds thicker than



a) Direct measurement of aspect ratio.
b) Initial random distribution of sand volcanoes showing no dependence of distance (x) on direction (θ).
c) Surface after deformation showing statistical dependence of distance on direction.
d) Example of data from Goldenville sandstone, showing x plotted against θ in cartesian and polar co-ordinates. Superimposed ellipse is drawn for a strain ratio of 2.00.

Figure 11. Estimation of the strain ratio from sand volcanoes. (After Ramsay, 1967).

50cm occur occasionally, and are distinguished by very thick, ripple-laminated c divisions, passing gradationally into finely crosslaminated cleaved siltstone (Fig. 14). In contrast, occasional very thin sand beds appear sharp-topped and ungraded. Closer examination reveals graded sandy slate above these; grading is marked by upward decrease in the proportion of sand grains immersed in fine slate. Both variants probably reflect variations in the texture of the sediment supplied to the turbidite. An abundance of silt produces thick, continuously graded units, whereas a bimodal sediment lacking very fine sand and silt components produces an apparently sharp-topped bed.

Laminated to massive sandstone

Beds classified by us as laminated to massive sandstones form the most abundant facies in most sections. They range in thickness from 20cm to about 6m; beds in slate-rich sequences are typically 40cm to 1m thick whereas thicker beds (1-6m) are more common in major sandstone-dominated packages.

In contrast to the previously described facies, they are poorly graded, with normal grading being confined to the top few centimetres of the bed. Most beds of this facies may be divided into a lower, generally laminated portion, and an upper portion in which any original lamination has been disturbed or obliterated. The top surface may bear ripples or sand volcanoes. Within this basic pattern, a number of variations are observed (Fig. 22). When underlain by slate the lower surfaces of the sand beds generally display groove casts (Fig. 15) and less commonly flute casts. Larger erosional scours occasionally occur at basal surfaces; these features were termed channels by Harris (1971), but we restrict the term channel to larger-scale vertically persistent features comparable to the channels described from modern submarine fans. In sandstone-dominated packages, beds of this facies are commonly amalgamated; individual layers may be difficult to separate under these circumstances.

Table 1 Facies features

SANDSTONE FACIES	
Graded sandstone	Thin (1-50cm) sandstone beds showing normal grading and Bouma sequence structures
Laminated to massive sandstone	Beds 20cm to 6m thick; generally with a laminated basal portion and a massive or piped upper part. Grading confined to the top few cm.
Internally scoured sandstones	50 cm to 10m thick amalgamated sandstone units with internal scours (scoop structures) and cross-stratification.
Muddy sandstone	Heterogeneous very poorly sorted sediments with slaty cleavage. Often contains slate intraclasts and/or folded laminae of sandstone.
Intraclast conglomerate	Medium to very coarse sandstone with over 50% by volume of large (2cm-1m) slate blocks.
Cross-stratified sandstone	Rare tabular cross-beds of pale sandstone, 0-50cm thick.
SLATE FACIES	
Crosslaminated slate	Cleaved siltstones with ripple crosslaminations.
Laminated slate	Fine grained parallel laminated and homogeneous slates.

Laminations in the bottom parts of the sandstone beds are generally parallel or subparallel. Lineations which resemble primary current lineation are often seen on the lamination surfaces, but it is generally difficult to distinguish with certainty whether such lineations are sedimentary or tectonic in origin. Nevertheless, the horizontal laminations are believed to represent upper flow-regime plane bed deposition of medium to fine sand. Wavy laminations and low-angle crosslaminations occur in some beds (Fig. 16). Both concave-upwards and convex-upwards laminations have been observed. These structures clearly represent low-amplitude bedforms of some sort, but their three-dimensional form cannot be determined in the Meguma rocks. In some cases they resemble "hummocky-cross-stratification" described from wave-influenced sandy storm deposits by Harms et al. (1975), Dott and Bourgeois (1982) and others. Hummocky cross-stratification is distinguished by a lack of preferred orientation in the dipping laminations, in contrast to conventional foreset crossbedding. Without extensive undeformed exposure of bedding surfaces, it may not be possible to distinguish hummocky cross-stratification from other forms of low-angle lamination such as antidunal crosslamination. This is the case in the Goldenville Formation, where the beds are usually exposed only in strike-parallel cross-section. However, where low angle crosslamination can be demonstrated, grooves and flutes from the bases of the beds indicate a unimodal eastward current flow, in contrast to the varied directions which would be expected from wave-induced currents (Seilacher, 1982). In the light of these observations, we believe that these structures are products of unidirectional flow and not of wave action.

Inverse grading occurs in the basal 5 to 10cm of some laminated to massive sandstone beds. Inverse grading may be due to steadily increasing current velocity, to variations in the sediment supplied, or to dispersive pressure resulting from grain collisions in the flow (Bagnold 1956). Dispersive pressure is probably not the main mechanism of grain support in these beds, howeveer, since such "grain flows" are usually deposited by "freezing" of the entire flow, and do not develop closely spaced parallel laminations.

The upper parts of laminated to massive sandstone beds commonly display a variety of postdepositional sedimentary structures. These include dish structures, sand pipes, sheet structures, convolute laminations and pseudonodules. Sand pipes (Fig. 17) are generally flattened cylindrical rods of slightly coarser and/or better sorted sand than their matrix. They are most frequently straight to slightly sinuous, and oriented at high angles to bedding, but horizontal, sinuous and contorted pipes are also seen. Pipes are generally 10-30cm long, but occasional examples may be over 1m in length. Some pipes are noticeably stained by iron oxide on weathered surfaces. In general it is difficult to determine whether these structures are organic or inorganic in origin. Figure 18 shows an example of a structure which is believed to be a burrow, because of downward deflection of the lamination. Long, straight, iron-stained pipes are possibly also burrows. The more common diffuse, unstained pipes appear to us more closely to resemble dewatering pillars. They would indicate sites of upward water-escape from a sand bed that had been rapidly deposited trapping water in a loosely packed configuration of grains. The common association of pipes with other dewater-

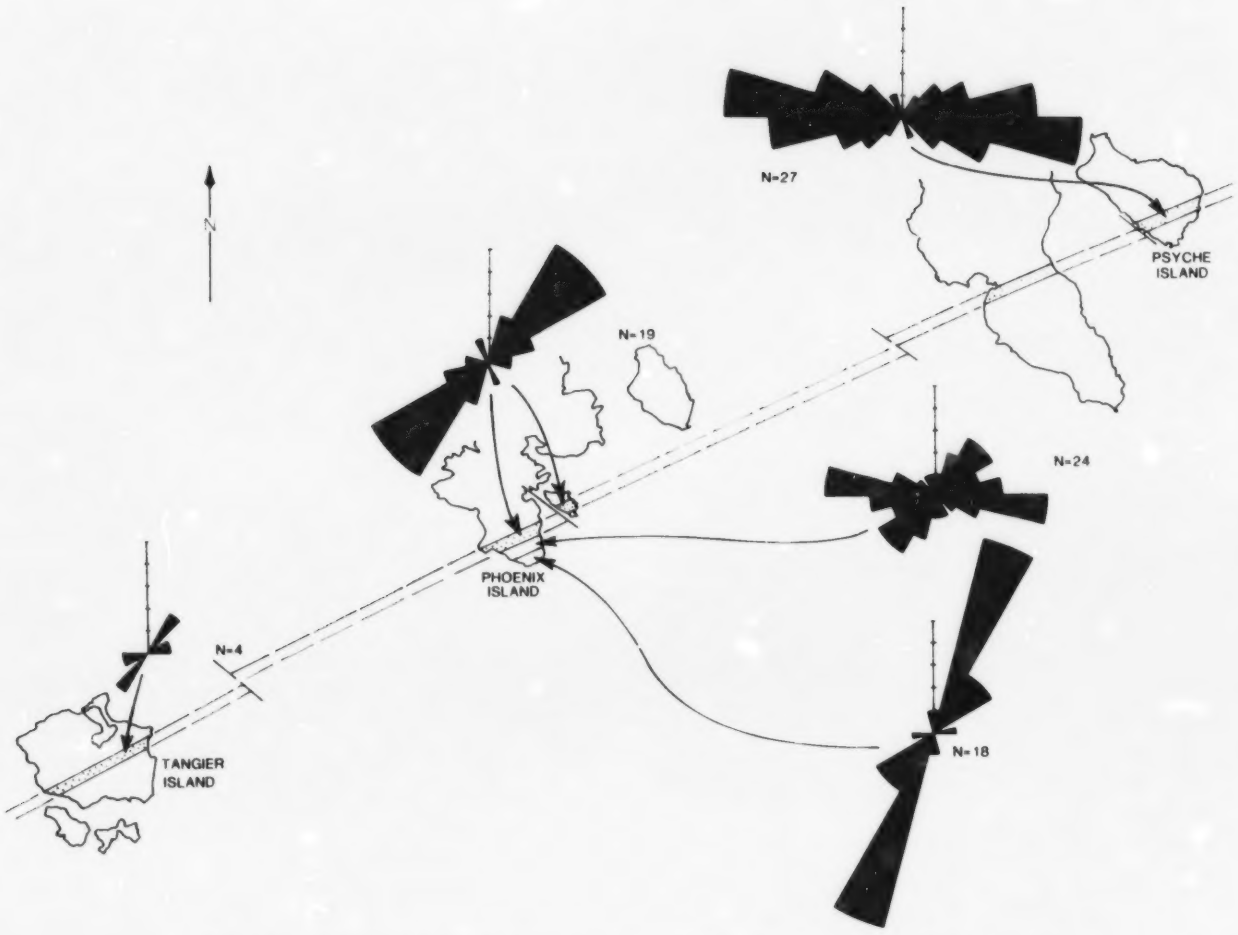


Figure 12. Paleocurrent rose diagrams showing variation in direction horizontally within unit E (stipple) and vertically in a single sequence on Phoenix Island. Rose diagrams are constructed from groove and flute orientations on the bases of sand beds.

ing structures such as dish structures and convolute lamination supports this interpretation. In occasional beds, pipes consistently are inclined to bedding surfaces when viewed on strike-parallel sections (Fig. 19), suggesting that shearing of partially fluidized sand occurred due to currents flowing immediately above. The sense of shearing is invariably eastward, consistent with the mean paleocurrent flow.

Sheet structures are planar features again consisting of coarser and/or better sorted sand than their matrix. Sheets are commonly densely spaced in layers 2 to 15cm thick within the upper parts of the thicker sand beds of this facies (Fig. 20). When the sheet-layer is thick, sheets are often seen to bifurcate downwards. Closely similar structures are described by Wood and Smith (1958) and Laird (1970) in rapidly deposited sandstones. They are interpreted as dewatering structures; the orientation of the sheets was possibly controlled by primary current lineation which existed in the sandstones before dewatering.

In some cases, the upper portions of sandstone beds are apparently homogeneous, lacking sheets and pipes.

Slate intraclasts, and pseudonodules of coarser or finer sandstone with contorted lamination occur in some of these beds. The pseudonodules represent laminated sand or sand volcanoes which were probably originally present at the top of the bed (see below); after deposition, the loosely packed central part of the bed underwent dewatering and was temporarily fluidized; pseudonodules of the more tightly packed sand at the top of the bed then sank into the fluidized layer.

In some beds traces of convolute lamination are present throughout the upper part. These beds probably underwent less complete fluidization, allowing some preservation of the original lamination.

A variety of structures are developed at the top of laminated to massive sand beds. Most common are ripples and sand volcanoes. Ripples may be straight-crested, linguoid or lunate in plan, and are developed in fine to very fine sandstone. The transition to overlying slate or muddy sandstone may be sharp, or gradational through 1 to 6cm of crosslaminated silt.

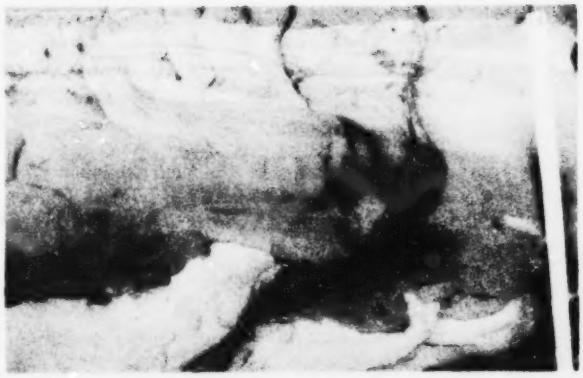


Figure 13. Graded sandstone bed with Bouma (1962) sequence sedimentary structures, and load structures at base. Tangier Island.

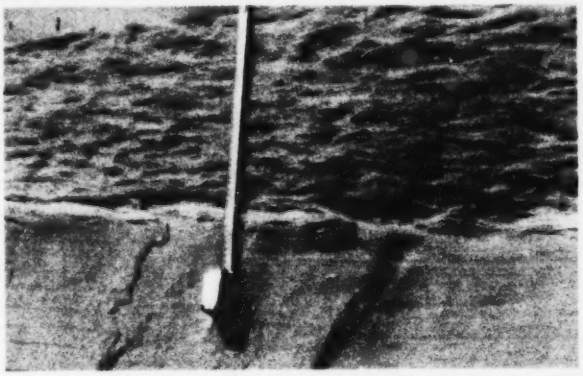


Figure 14. Graded sand bed showing thick upper ripple-crosslaminated division. Phoenix Island, west coast.

Sand volcanoes (Fig. 21) are extremely common in the Goldenville Formation. Both concentric and radial types of internal structure are seen. Typical concentric volcanoes show laminations dipping gently outwards on the flanks of the volcano and steeply into the central pit. In a few cases where volcanoes are favourably exposed in cross-section we have been able to observe a central feeder sand pipe. Radial structure is most easily seen in weathered sand volcanoes exposed in horizontal cross-section. Radiating zones are marked by slight variations in grain size and sorting.

Sand volcanoes in the Goldenville Formation have been interpreted both as biogenic structures (*Astropolithon hindii*; Dawson, 1890) and as inorganic products of dewatering (Pickerill and Harris, 1979).

Because of their close resemblance to other examples of sand volcanoes produced by dewatering (e.g. Rettger, 1935) we favour inorganic formation, but a biogenic origin cannot be completely excluded. Concentric structures are clearly due to slight variations in the velocity of expelled water, leading to the deposition of laminae of varying grain size around the central vent. Radial structures are more difficult to explain. They may be due to: (1) development of small scale grain flows analogous to lava flows on the flanks of a volcano (2) radial fracturing of semi-brittle sand in response to a build-up of hydraulic pressure in the base of the volcano (R. Pickerill, personal communication, 1984); or (3) later pervasive dewatering, developing

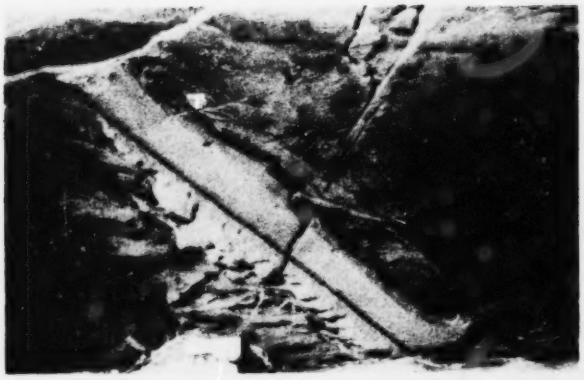


Figure 15. Intersecting groove casts on base of sandtone bed. Liscomb Island.

sheet structures in the sands of the volcano, with the orientation of the sheets being controlled by a radial primary current lineation, as postulated above for sheet structures elsewhere in laminated to massive sand beds.

Parallel laminations are sometimes present at the top of thick (2-6m) laminated to massive sandstone beds. This uppermost laminated section may be noticeably better sorted than the underlying dewatered section. Cross-stratified sandstone (recognized as a separate facies — see below) may occur at this position. When present, this upper laminated portion must represent a return to slower deposition and traction sedimentation under the influence of still rapid currents.

Laminated to massive sandstones resemble beds interpreted as fluidized flow deposits by Middleton and Hampton (1973). They are equivalent to facies B sandstones in the submarine-fan models of Walker and Mutti (1973) and Ricci-Lucchi (1975). More recently, Lowe (1982) has described closely similar, though generally coarser units as products of high density turbidity flow. This interpretation is futher discussed in a later section.

Internally scoured sandstone

Internally scoured sandstones are abundant in sandstone-dominated packages. Individual sand layers are commonly amalgamated, lacking intervening slate beds. Figure 23 shows a typical sequence from a sandstone-dominated package, which may be subdivided into a basal laminated section, a central internally scoured portion and an upper section which resembles the upper parts of the laminated to massive sandstone beds described above. As in the case of laminated to massive sandstones, a number of variations on the basic sequence occur. The basal laminated section is frequently absent. It is possible that the complete sequence shown in Figure 23 represents two depositional events, the lower part being a laminated to massive bed which has been truncated by a more energetic flow.

Internally scoured sandstones show all the structures displayed by laminated to massive sandstones—parallel and low angle crosslaminations; intraclasts, pipes, sheets, dish structures, pseudonodules, sand volcanoes and ripples. They are distinguished by the occurrence of spectacular internal scour surfaces here termed scoop structures and by the associated development of cross-stratification. In addition, horizontally stratified parts of these beds frequently show rather distinctive widely spaced (1-10cm) lamination or layering defined by slight variations in grain size.

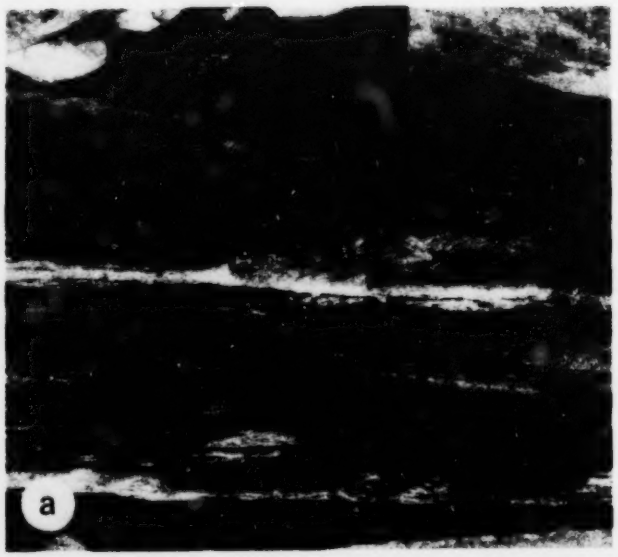


Figure 16a. Typical appearance of laminated to massive sandstone bed. Note wavy laminations in basal portion. Phoenix Island. Pencil 14cm.

Figure 16b. Dish structure in laminated to massive sandstone. Tangier Island.

Figure 16c. Sandstone with pipes overlying irregular laminations. Tangier Island.

Figure 17. Laminated to massive sandstone showing sand pipes and sand volcanoes (white lenses at top of bed). Tangier Island.

Figure 18. Burrow in laminated sandstone. Phoenix Island, west coast. Pencil is 15cm long.

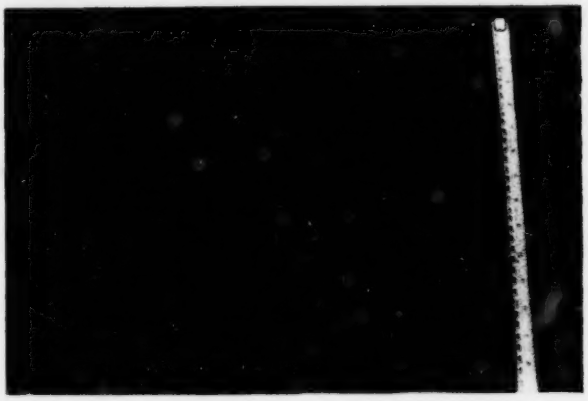


Figure 19. Sandpipes inclined to bedding. Phoenix Island.

Figure 20a. Sheet structures seen from top surface of bed. Taylor Head, west coast.

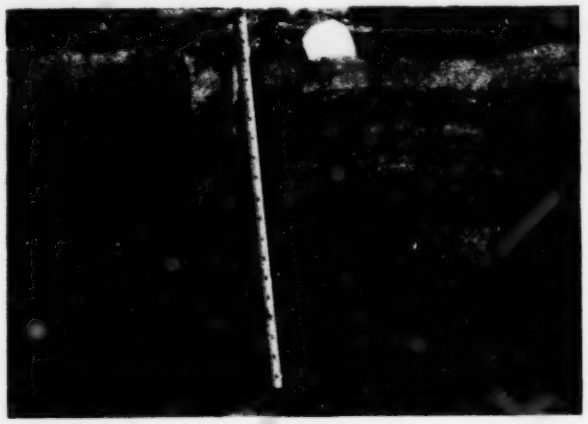


Figure 20b. Sheet structures bifurcating downwards in sand beds.

Figure 21. Sand volcanoes on top surface of sandstone bed. Taylor Head, west coast.

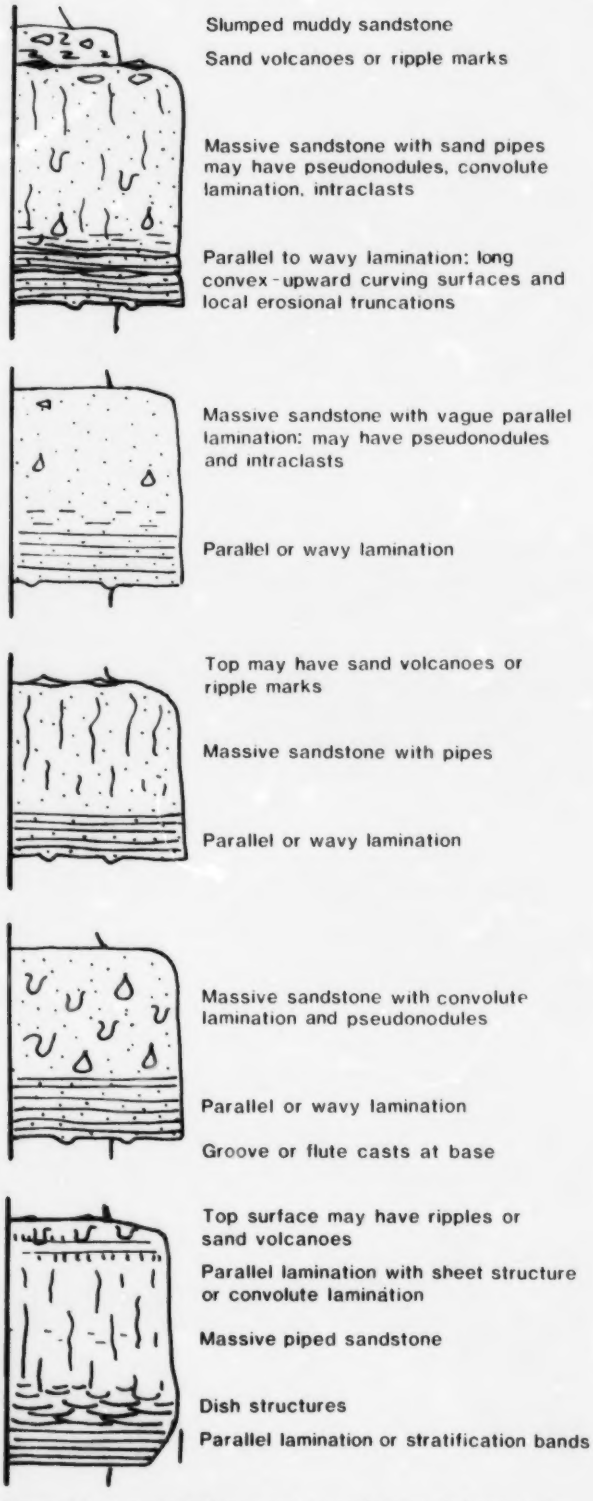

Slumped muddy sandstone
Sand volcanoes or ripple marks
Massive sandstone with sand pipes may have pseudonodules, convolute lamination, intraclasts
Parallel to wavy lamination: long convex-upward curving surfaces and local erosional truncations
Massive sandstone with vague parallel lamination: may have pseudonodules and intraclasts
Parallel or wavy lamination
Top may have sand volcanoes or ripple marks
Massive sandstone with pipes
Parallel or wavy lamination
Massive sandstone with convolute lamination and pseudonodules
Parallel or wavy lamination
Groove or flute casts at base
Top surface may have ripples or sand volcanoes
Parallel lamination with sheet structure or convolute lamination
Massive piped sandstone
Dish structures
Parallel lamination or stratification bands

Figure 22. Laminated to massive sandstones. Schematic section illustrating variability in vertical sequence.

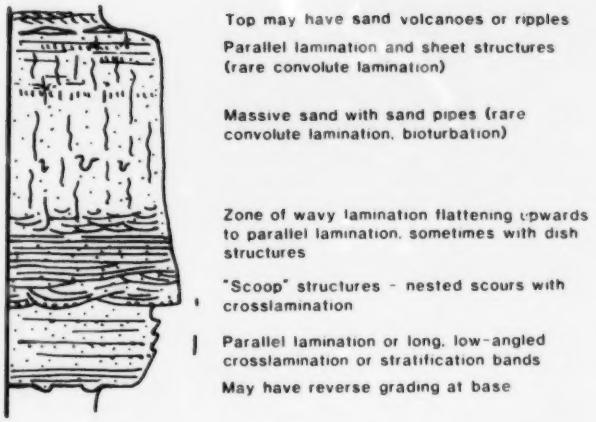

Top may have sand volcanoes or ripples
Parallel lamination and sheet structures (rare convolute lamination)
Massive sand with sand pipes (rare convolute lamination, bioturbation)
Zone of wavy lamination flattening upwards to parallel lamination, sometimes with dish structures
"Scoop" structures - nested scours with crosslamination
Parallel lamination or long, low-angled crosslamination or stratification bands
May have reverse grading at base

Figure 23a. Typical sequence of internally scoured sandstone facies.

Figure 23b. Internally scoured sequence; laminated lower unit, scoured middle portion with cross-beds, upper unit with pipes. Sandy Cove Point.

Scoop structures are upwards-concave scours cut into sandstone, which average about 15cm deep, 35cm wide and about 1m long in their deformed state. They resemble large flutes in shape, generally having a more bulbous up-current end (Fig. 24) but are more widely flared than the flutes cut into slate. Generally they do not appear to be organized in discrete horizons but instead are developed throughout a vertical interval from 20cm to 2m in thickness. They cannot therefore be attributed to amalgamation of a series of sand beds with large flutes at the base of each. Instead, they appear to be intermediate between true flutes and dunes. Each scoop was initiated as a large flute-like scour, and filled by a drape of laminated sand which progressively smoothed out the bed. This sand is invariably coarser grained than sands above and below the scooped interval. Very coarse sand and granule material is usually concentrated at the base of each scoop, but may be scattered throughout the scoop fill. During filling, forward migration of the up-current lip of the depression sometimes resulted from deposition on the lee slope, producing a "climbing" cross set as shown in Figure 25; however, unlike normal dunes, the scoop structures did not migrate far enough to produce typical trough cross-stratification, although later scoops are sometimes cut into fills of earlier scoops. Long axes of scoops invariably have low pitch on bedding, and scoop-fills indicate eastward paleocurrents, consistent with directions indicated by sole marks.

Laterally extensive inclined erosion surfaces are closely associated with scoop structures in some large packages. Figure 26 shows one such erosion surface that climbs from west to east (down-current) within a thick sand layer. Figure 27 shows another such erosion surface that appears to have developed from a number of linked scoops. Scoop structures are generally overlain by wavy laminations which gradually smooth out the bed topography. Laminations give way in the upper part of most beds to massive sandstone with pipe and sheet structures.

Cross-stratification and internal scouring are reported from lower part of "proximal" sediment gravity flow deposits by Mutti and Ricci-Lucchi (1972), Aalto (1976) Walker (1978), Siemers (1981), and Lowe (1982). Hiscott and Middleton (1979; Fig. 11) show in cross-section structures apparently identical to the Goldenville scoop structures. These structures are recorded by them to occur in 12 per cent of sandstone beds in the Tourelle Formation in Quebec. We conclude that these structures are in fact common in thick sandstone beds deposited by high-energy sediment gravity flows. They clearly indicate traction sedimentation, as opposed to direct dumping of suspended material.

Stratification bands (Fig. 28) from 1 to 10cm thick, defined by variations in grain size, often occur in the lower, horizontally stratified parts of internally scoured sandstones, but are also recorded in thick laminated to massive sandstones. Both normal and inverse grading patterns are seen in these bands, but the strongest variations in grain-size occur in inversely graded layers. These layers closely resemble "near-horizontal stratification" described by Hiscott and Middleton (1979) from the Tourelle Formation of Quebec, and by Lowe (1982) from the Precambrian Thunderhead Sandstone of Tennessee. They are interpreted as *traction carpets*, produced by grain flow at the base of high-concentration turbidity currents. This interpretation is further discussed below.

Muddy sandstone

Very poorly sorted mixtures of sand and fine-grained material that show slaty cleavage are classified by us as muddy sandstones, even though some would be more correctly described as sandy mudstones. In addition to poor sorting, these sediments are generally distinguished by small scale intrafolial folds and abundant intraclasts. Pseudonodules of coarse sand may also be present (Fig. 29). Muddy sandstones occur in beds from 10cm to 1m thick, most frequently overlying sandstone (particularly the laminated to massive type), and underlying slate, or less commonly with slate above and below. They are rare within sandstone-dominated packages. The muddier more homogeneous units show matrix-support of sand grains, suggesting that the mud matrix had sufficient strength to support sand during flow. These units would therefore be cohesive *debris flows*. Less homogeneous units show very thin sandstone beds in various stages of folding and mixing with mud confirming that the matrix is original material and not just degraded lithic fragments. We believe these beds represent slumped units of originally interbedded sand and mud. Systematic measurement of fold hinge directions to determine paleoslope is precluded by the strong cleavage. The effects of tectonic strains in reorientating these folds cannot be determined.

These units closely resemble slurry sandstones described by Wood and Smith (1958) and Hiscott and Middleton (1979). They correspond to facies F in the submarine fan model of Walker and Mutti (1973).

Intraclast conglomerate

Intraclast conglomerates are rare in the Goldenville Formation, but examples have been recorded from widely scattered locations (Psyche Island, Taylor Head, Indian Harbour). They consist of interspersed, irregularly shaped bodies of slate and medium to very coarse sandstone or granule conglomerate which range from a few centimetres to over one metre in diameter. Sandstone bodies sometimes show re-entrant angles, while individual slate masses, where distinguishable, have block or slab-like outlines (Fig. 30). This indicates that these beds consist of slate intraclasts immersed in a sandstone matrix. Laminations are sometimes preserved within the block which have been flattened during later tectonic deformation. A transition from sandstone with intraclasts into intraclast conglomerate is seen in Figure 31, confirming the interpretation. Nevertheless, the nature of these beds is far from obvious in most outcrops; Harris (1971) interpreted them as slump breccias in which slate was the matrix material.

Intraclast conglomerate layers vary from 1 to 10.5m in thickness and occur in sandstone-dominated packages. Within a layer, intraclast-free beds of coarse laminated sandstone sometimes occur; these are laterally discontinuous over distances of a few metres. Intraclast conglomerates may be associated with coarse, cross-stratified sand. Figure 32 shows an example exposed immediately below intraclast conglomerate from Outer Island.

Intraclast conglomerates clearly record massive erosion of fine-grained sediment by high-energy currents transporting coarse material. The fine-grained sediment must have been at least partially lithified to survive as large, sharply bounded blocks. Interruptions in the supply of shale blocks led to the deposition of laminated or cross-stratified sand by traction currents.

Cross-stratified sandstone

Beds classified by us as the cross-stratified sandstone facies are extremely rare in the Goldenville Formation, being recorded at three localities only. They are distinguished as a separate facies because of their distinctive lithological and sedimentary features, which suggest deposition by persistent dilute traction currents.

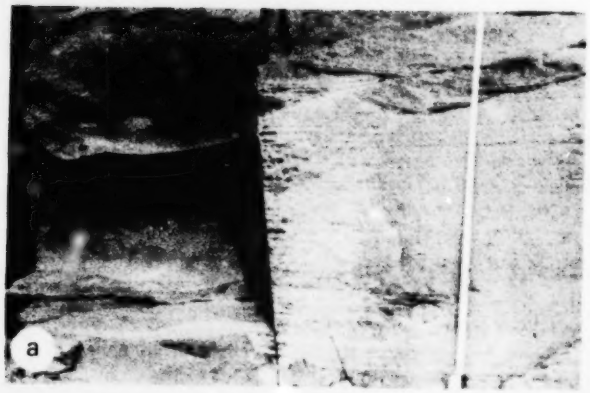


Figure 24. Scoop structures

a) Profile view of scour and cross-stratified fill. Sandy Cove Point. Scale 1m.

b) Profile view on steeply dipping beds, Crooks Island. Current flowed away from camera.

c) Underneath view of sand bed with scoop structures. Hammer for scale (top right). Dipper Cover.

d) Top view of exhumed scoured surface. Sandy Cove Point. Tape: 2m.

e) Wavy-laminated sandstone infilling scoop structures. Gerard Island. Matchbook 5cm (lower centre).

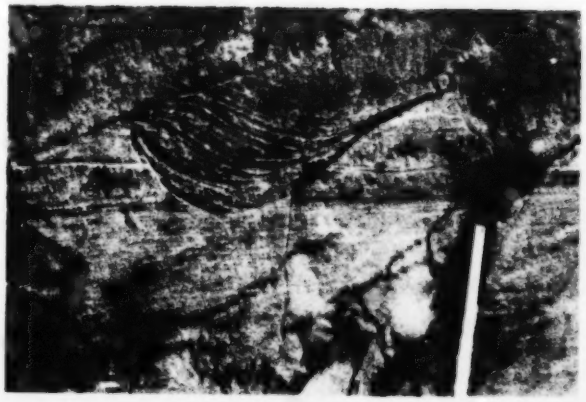


Figure 25. Cross-stratified sandstone filling scoop structure. East is to the right. Gerard Island.

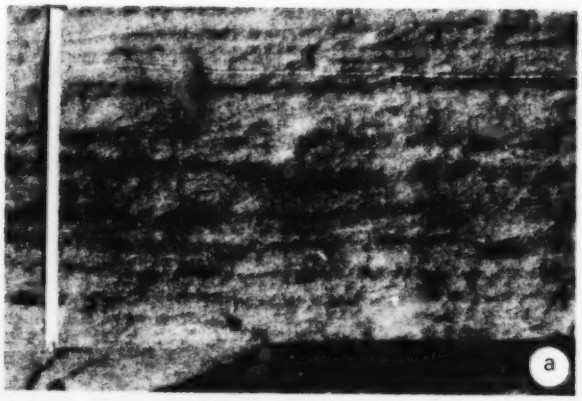


Figure 26. Erosion surface within massive sandstone beds. Sandy Cove Point.

Figure 27. Erosion surface developed in association with scoop structures. Gerard Island. Same outcrop as Figure 25.

Figure 28. a) Typical appearance of "stratification bands' interpreted as traction carpet deposits. Dipper Cove.
b) Inversely graded stratification bands. Phoenix Island, west coast.

Figure 33 shows a tabular sandstone cross-set from Crooks Island (Fig. 1) distinguished from adjacent laminated to massive sandstone by pale colour due to its relatively well-sorted quartz-rich composition. The bed is better sorted than the adjacent sandstones, but in thin section is seen nevertheless to contain appreciable amount of fine-grained matrix.

The crossbed in Figure 33 shows a westward component of paleocurrent flow; other examples show eastward paleocurrents, however. A main tabular cross-set, which varies from zero to 30cm thick when traced laterally over 10m, is capped locally by smaller scale trough cross-sets. Further to the west, a second lenticular unit of this facies occurs at the same horizon.

Figure 34 shows a second example from Dipper Cove, which occurs near the top of a sandstone-dominated package. The cross-stratified unit is broken into a series of overlapping sand lenses by parting surfaces on which small-scale ripples are seen.

The cross-stratified sandstones are interpreted as deposits of more steadily flowing currents than other Goldenville sandstones.

The example from Crooks Island (Fig. 33) represents a series of "starved" sand waves and dunes of relatively well sorted sand which migrated from east to west. Deposition of the cross-stratified sandstone on Dipper Cove Island (Fig. 34) was probably less continuous; rippled parting surfaces presumably represent episodic deceleration and acceleration of the depositing current.

Almost identical cross-stratified sandstones interbedded with turbidites have been recorded by Hiscott and Middleton (1979). They appear to be equivalent to facies E of Mutti and Ricci-Lucchi (1972) who interpreted this facies to represent products of "flow by-passing" at the ends of submarine-fan channels; according to this interpretation a sand layer deposited from a turbidity current is reworked by the tail of the same current. Our observations suggest that the crossbedded sandstone cannot be regarded as deposits of single turbidite events. We interpret them as products of reworking of the sediment by more continuously flowing bottom currents.

Crosslaminated slate

Slates showing ripple crosslaminations (Fig. 35) are relatively coarse grained, consisting mostly of silt-size material. They are generally interbedded with finer-grained laminated or homogeneous slates. Crosslamination is most commonly developed in thin (1-5cm) graded silt layers within which climbing ripples commonly pass upwards into starved ripples. Crosslaminations commonly indicate an eastward component of paleocurrent flow. Sometimes a thin layer of sandstone is present at the base of such layers; these units are transitional to the graded sandstone facies, and probably represent low-energy turbidity currents. Less commonly, ripple crosslamination is developed throughout a thick (10cm to 2m) interval of cleaved siltstone. The significance of these units is uncertain; like the cross-stratified sandstones they probably represent intervals of steady bottom-current flow, but there is insufficient evidence to indicate whether such currents flowed parallel to or across the paleoslope.

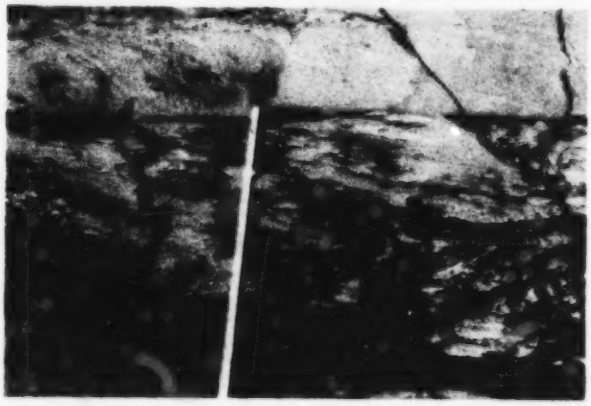


Figure 29. Muddy sandstone facies: thin folded laminae of sandstone (lower right) and sandstone pseudonodules (pale) in slate. Gerard Island.

Laminated slate

Grey-green slate beds occurring between the other facies either show parallel laminations or are apparently homogeneous. Thick slate intervals frequently show a gradual upward decrease in the abundance of coarser laminae. Diffuse carbonate concretions occur occasionally; fine fossil debris was recovered from the outcrop shown in Figure 37. Because of the intense cleavage development and metamorphic recrystallization in the slates, less is known of their primary composition and sedimentary structures than other facies.

Muddy sediments between turbidite sand units may be products of suspension sedimentation from the tails of turbidity currents, they may be fallout from turbid interflows, or they may represent steady state hemipelagic deposition. A variety of terminologies have been suggested for these muds, which represent the Td and Te divisions of the Bouma (1962) sequence. Poor exposure in the Goldenville Formation slates generally precludes any systematic subdivision. We suspect that slates include both turbidite and steady-state suspension deposits.

Very rare isolated pebbles of white vein quartz occur immersed in slate (Fig. 36). They are well rounded and clearly distinct from the later quartz veins which cut both slate and sandstone. We interpret these as dropstones derived from floating ice, indicating a polar environment. This would be consistent with available reconstructions for the location of the Meguma zone in Cambro-Ordovician time. Dropstones derived from a glaciated terrain would be expected to show a variety of lithologies, but only quartz pebbles have been recorded to date; the reason for this uniformity is unknown.

Sandstone dykes occur locally in slate intervals that are 0.5m or more in thickness. Unlike sand beds, they are almost invariably tightly folded, presumably reflecting an original orientation at high angles to bedding, causing them to buckle readily during deformation; veins in this orientation are also buckled when they pass through slate. Sandstone dykes were presumably formed when sandstone beds underwent fluidization at some stage after deposition, and sand was injected into fissures in adjacent mud, suggesting that overpressuring occurred during burial.

Depositional mechanisms of the sandstsones

With the exception of rare cross-stratified sandstones, the Goldenville sandstones were clearly laid down by episodic high-energy events which transported and deposited large volumes of sediment. Such processes fall into two categories: storm events affecting the continental shelves and sediment gravity flows operating on slopes.

The products of these two types of process may be difficult to distinguish (Nelson, 1982). Some sequences in the Goldenville Formation containing abundant laminated to massive sandstone beds resemble in their general stratification sequence storm deposits

Figure 30. a) Typical appearance of intraclast conglomerate. Psyche Island.
b) Close-up of intraclast conglomerate showing blocks of slate (darker). Indian Harbour.

described by Hunter and Clifton (1982) and Dott and Bourgeois (1982), in which homogenization of the upper parts of sandstone beds is due to bioturbation, not dewatering. The presence of occasional definite vertical burrows (Fig. 18) might also suggest a shallow environment although vertical burrows have been recorded from turbidites elsewhere (e.g. Siemers, 1981). The following lines of evidence support an origin by sediment gravity flow; however:

1. Paleocurrent directions are strongly clustered and unimodal, whereas according to Seilacher (1982), storm deposits should show multidirectional sole marks on single beds. Although Walker et al. (1983) described beds with undirectional sole marks which they interpret as wave-influenced storm deposits, the general consistency of paleocurrent direction throughout the Goldenville, and the almost complete absence of westward currents, are difficult to reconcile with a shelf environment.
2. Wave ripples are absent from both the sands and the slates, whereas current ripples are abundant.
3. Trace fossils described by Pickerill and Keppie (1981) are consistent with a deep-water origin. Although some sand pipes have been compared with *Skolithos* (Harris and Schenk, 1975), characteristic of extremely shallow water, no trace fossils of the Cruiziana ichnofacies (Seilacher, 1967), normally associated with shelf storm deposits, have been described.

Figure 31. Discontinuous bed of laminated sandstone within intraclast conglomerate. Top left of photograph shows boundary between sandstone and intraclast conglomerate. Psyche Island.

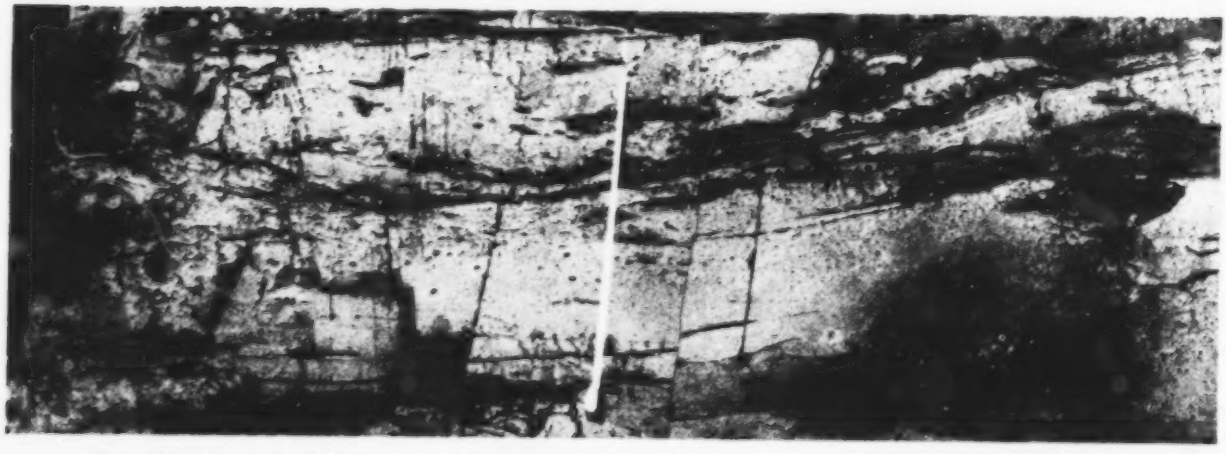


Figure 32. Cross-stratified coarse sandstone immediately underlying intraclast conglomerate bed on Outer Island.

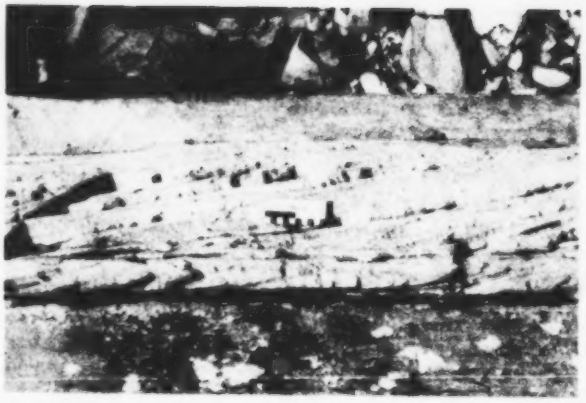


Figure 33. Cross-stratified sandstone facies. Tabular cross set of quartzose sandstone. East is on the right. Crooks Island.

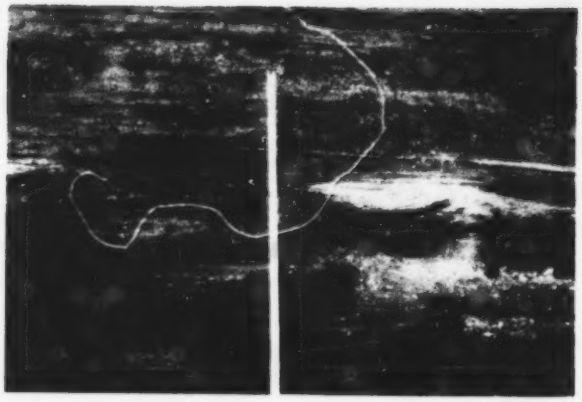


Figure 36. Laminated slate with coarser calcareous lens (right of centre) from which fossils debris was recovered. Phoenix Island, east coast.

Figure 34. Cross-stratified sandstone, Dipper Cove. Rippled surfaces marked by conspicuous parting separate lenticular bodies of laminated sandstone.

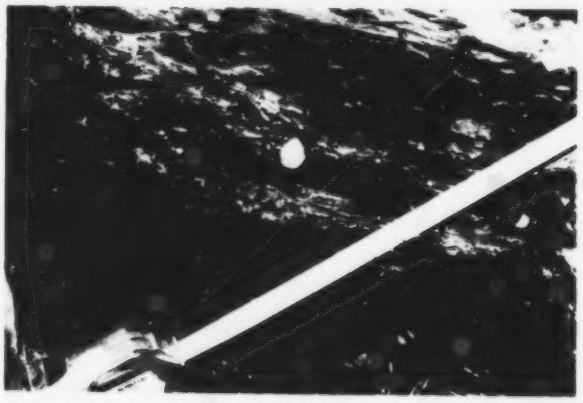


Figure 37. Slate with isolated pebble of white vein quartz, interpreted as a dropstone. Psyche Island.

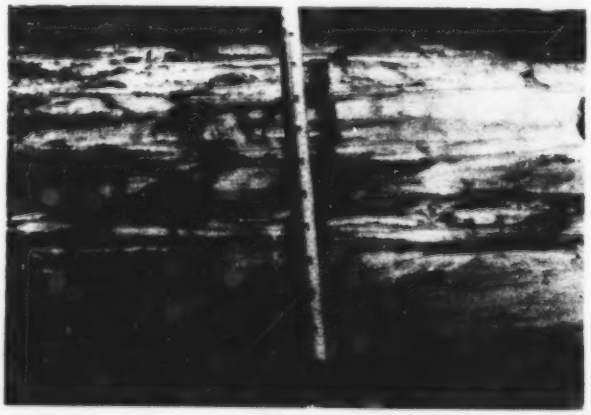


Figure 35. Typical appearance of crosslaminated slate facies. Psyche Island.

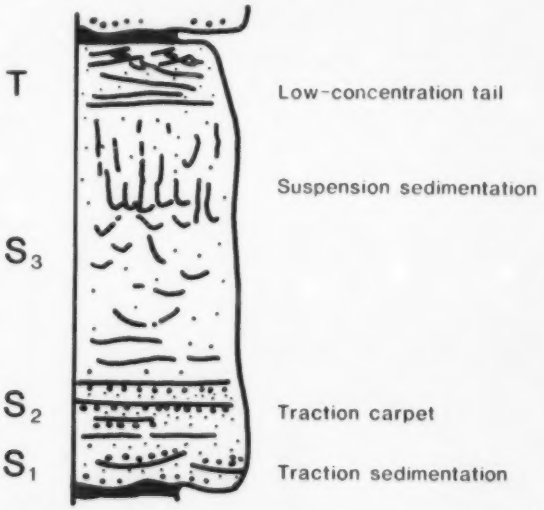


Figure 38. Typical sequence developed from high density turbidity current, (after Lowe, 1982).

4. Bioturbation was not seen in the slates between sandstone beds.
5. Climbing ripple crosslaminations are common whereas storm graded sand beds commonly show only trough-crosslamination (Nelson, 1982).
6. Thick, localized sand bodies occur in the Goldenville Formation, consisting of internally scoured and laminated to massive sandstones, and showing thinning and fining-upwards megasequences. These are interpreted as submarine channel fills. Inshore channel fills typically consist of homogeneous trough-crosslaminated sand without fining-upwards cycles or vertical sequences of sedimentary structures (Nelson, 1982).
7. Slump structures and slurried bedding indicate remobilization of sand and mud slopes, and are distributed throughout the Goldenville Formation.
8. It is difficult to envisage a deposit as thick as the Goldenville Formation being laid down under wave-influenced shelf conditions without showing some transition to a littoral or subaerial environment.

Mechanisms of sediment gravity flow

Middleton and Hampton (1973) classified mechanisms of sediment gravity flow into four theoretical types, based on the process responsible for supporting grains within the flow. The four possible processes are (1) turbulence, (2) upward flow of expelled pore fluids, (3) grain interaction, and (4) matrix strength. The corresponding types of flow are known as (1) turbidity currents, (2) liquefied or fluidized flows, (3) grain flows and (4) cohesive debris flows.

Only fluid turbulence and matrix strength are well documented as support mechanisms in natural flows responsible for large-scale sediment transport. Calculations based on the known properties of fluidized sediment (Lowe, 1976b; Hiscott and Middleton, 1979) indicate that fluidized flows will become turbulent at low velocities, and will therefore tend to degenerate into high-density turbidity currents. Grain flows are considered theoretically by Lowe (1976a), who demonstrates that sandy grain flows are generally less than 5cm thick, and require steep slopes (18° or more) for movement if gravity is the only driving mechanism. Such slopes are rare in most subaqueous environments. Thus only cohesive debris flows and turbidity flows can be regarded as major *transporters* of sediment over long distances on submarine slopes. However, grain flow and fluidization may play a role in *deposition* of sediment from turbidity flows.

Three styles of deposition from turbidity currents are recognized. *Traction sedimentation* occurs when the flow transports a thin load of sand grains, producing laminations in the deposited sediment. Interaction of the flow with the bed may produce bedforms such as ripples or dunes. Traction deposition was clearly responsible for the lower parts of the Goldenville laminated to massive and internally scoured sandstone beds, and for the laminated 'b' division of graded sand beds.

Suspension sedimentation occurs when sediment fallout from the flow is fast, preventing the development of bedload. Structureless loosely packed sandstone is deposited by this mechanism, but frequently undergoes spontaneous dewatering, with the production of dish and pipe structures. Suspension deposition produced massive sandstone with pipes and sheet structures that forms the upper part of most internally scoured and laminated to massive sandstones, Bouma 'a' divisions of graded sandstone beds, and laminated to homogeneous slates between sand beds are probably also products of suspension sedimentation.

An intermediate stage known as *traction carpet sedimentation* (Dzulynsky and Sanders, 1962) occurs between traction and suspension sedimentation in some high density turbidites (Hiscott and Middleton, 1979; Lowe, 1982). A traction carpet is developed when coarse suspended sediment becomes concentrated toward the base of the flow. Dispersive pressure due to grain collisions becomes important in grain-support. Dispersive pressure is greater for coarse particles (Bagnold, 1956) and produces an inversely graded layer. Deposition occurs by collapse and "freezing" of the traction carpet which is effectively a grain flow. Unlike an isolated grain flow, however, it may remain in motion on a gentle slope, due to the stress applied by the fast-moving turbulent flow above. Successive traction carpets may develop at the base of a flow, producing stacked stratification bands.

Early work on turbidity currents emphasized a distinction between low density and high density turbidity flows. Low density flows are characterized by distribution grading, whereas high density flows display coarse-tail grading, in which only the coarser size-fraction is graded. Deposits of low density turbidity currents are well known from laboratory experiments and natural examples, both modern and ancient. They show a characteristic sequence of sedimentary structures identified by Bouma (1962) and described as the Bouma sequence. High density flows, being harder to study have been relatively neglected until recently. Lowe (1982) has attempted to synthesize observations on natural "proximal" turbidite sandstones into a model for high-density turbidity current deposition. Lowe's analysis is based upon the recognition of three grain-size populations, which differ somewhat in their grain-support mechanisms and are deposited at different stages in the evolution of a flow. *Population 1* consists of clay, silt and fine to medium sand, which can be maintained in suspension by turbulence alone. Coarse sand to granule-size material of *population 2* requires support by a combination of fluid turbulence, hindered settling due to high grain concentration, and buoyant lift provided by an interstitial suspension of finer sediment. Hence these grains can only be transported in high density flows. *Population 3* includes pebble and cobble sized material which requires dispersive pressure from grain collisions to maintain grain-support. Population 3 sediments are coarser than any seen by us in the Goldenville Formation and will not be considered further.

Lowe's (1982) analysis of high density turbidity flow emphasizes that grain populations 1 and 2 are deposited somewhat independently of each other. Each population shows a transition from an early stage of traction sedimentation to a period of more rapid suspension sedimentation (Fig. 38); traction carpets are developed during the transition in population 2. Thus the classic Bouma (1962) sequence is regarded by Lowe as composite; the basal massive 'a' division represents the waning stages of suspension deposition of population 2, whereas the succeeding b,c, and d divisions are deposited by traction and then suspension deposition of population 1.

Our observations of Goldenville sandstones show a predominance of vertical sequences in which traction sedimentation gives way upwards into suspension sedimentation as described by Lowe (1982). Both laminated-to-massive and internally scoured sandstones show this type of sequence. Thin laminated and crosslaminated intervals at the top of such units may represent a return to traction sedimentation in a finer grained population, but our sequences do not precisely match those of Lowe in grain size. The Goldenville laminated to massive sandstones are generally finer than the otherwise similar population-2 beds of Lowe. We suspect

that a continuum of grain behaviour in fact exists and that segregation into distinct grain populations probably reflects in a complex way both the grain-size distribution of the sediment supplied at the source of the flow, and the slopes over which the flow moved. Population 1 in the Goldenville sandstones appears to include only the finest sand plus silt; fine to coarse sand behaves similarly to Lowe's population 2. Other differences between Lowe's (1982) sequence and that observed by us involve the position of traction carpet deposits. The inversely graded layers observed by us in internally scoured sandstones and more rarely in laminated to massive sandstones commonly occur near the base of a unit, and not at the transition from traction to suspension sedimentation as predicted by Lowe. In this they resemble the stratification bands described by Hiscott and Middleton (1979).

Lateral variability of single beds

Correlation by magnetic gradiometer shows that many of the sandstone-dominated packages in the Goldenville Formation pinch out or interdigitate with slaty facies. Where single sand beds can be traced along strike, they show changes in thickness and in their sequence of sedimentary structures. We shall show in a later section that many of the thicker sandstone bodies are fills of submarine channels. Because paleocurrent markers generally have significant pitch on bedding surfaces, we therefore infer that the observed variability of single sand beds generally reflects components of both down-current (longitudinal) and across-current (transverse) variation. Only in cases where paleocurrent flow was parallel to the present-day strike is a true longitudinal section of a flow expected; conversely, beds with steeply pitching paleocurrent markers offer the best view of transverse variability.

Different parts of the sequence studied by us show contrasting patterns of current flow. Thus the central part of magentic unit H (Fig. 6), shows an abundance of paleocurrent markers with near-zero pitch (Harris, 1971). Sandstone packages are seen predominantly in longitudinal view and show lateral continuity over distances of several kilometres; this enabled Harris (1971) to correlate laterally on the basis of lithology alone in this region. In contrast, mean paleocurrents in most of units D and E (Fig. 3, 4, 8) in the Phoenix Island area pitch significantly on bedding; in this area lateral facies changes are great. Thus we infer that most sandstone beds showed greater variation across-current than down-current. The situation is further complicated by variability in current direction between different locations on the same bed. Our reconstruction of down-current variation is therefore necessarily speculative.

Figure 39a illustrates the types of variability that are seen over short distances. Scoop structures above a major scoured surface may fade laterally into either parallel or subparallel laminations, or into massive sand with abundant sand pipes. Despite changes in sedimentary structures, horizons characterized by coarse sand and granule material appear to be relatively persistent when traced along strike.

Figure 39b shows that the thickness of sandstone beds and packages may change dramatically when traced distances of several kilometres along strike. Internally-scoured sandstone is frequently replaced laterally by laminated to massive sandstone, and the upper piped portion of the laminated to massive beds may disappear, leaving thin beds of parallel-laminated sandstone. Because sand beds are rarely exposed in longitudinal section, and because down-current variations were probably very gradual, down current variations are less easily observed than across-current variations. It is likely that internally scoured sandstones represent high energy flows, and pass down-current into generally thinner, finer, laminated to massive sandstones. These probably in turn pass into graded sandstone and eventually into crosslaminated slate. We suspect that these transitions occur over distances of several tens of kilometres down-current.

Along-strike variations are also seen in other facies. Muddy sandstone units are laterally discontinuous in slate-rich sequences, and frequently replace thin sandstone beds present elsewhere at the same horizon. This supports the interpretation of these beds as products of local remobilization and mixing of previously deposited sand and mud.

Intraclast conglomerates are highly lenticular units, as is apparent from their distribution in the measured sections. The intraclasts are products of erosion by single large events, and are probably formed during the cutting of the submarine channels, which are inferred to have controlled deposition of major sandstone packages (see below). However only one of the main occurrences is at the *base* of a sandstone package, where it would be expected if intraclast conglomerate formed during channel *initiation*. This suggests that the conglomerates were formed during channel *migration*, and were localized to areas of the channel margin undergoing erosion. Figure 9 shows the distribuiton of intraclast conglomerate, in a typical channel fill.

LARGE-SCALE FEATURES OF THE DEPOSITIONAL SYSTEM

A number of large-scale sedimentary features are conspicuous on the correlated stratigraphic sections (Fig. 4 to 7). Most obvious are thick (50-150m) sandstone bodies that are either lenticular or interdigitate with more slaty sequences over distances of several kilometres along strike. These are described as *major sandstone packages*. The slaty sequences themselves contain conspicuous thinner (5-20m) packets of sandstone that in some cases also disappear when traced laterally. However, because of their lesser thickness these have more tabular cross-sections than the thick packages. They are here termed *minor sandstone packages*.

In this section we discuss the origin of these sandstone-dominated units and the finer grained sequences between them, in relation to sediment dispersal patterns and the geometry of the depositional system.

Submarine fan models

Most modern subaqueous sediment gravity flow deposits are deposited in submarine fans but some ancient turbidite deposits formed in linear troughs or multi-source sediment aprons. Is the Goldenville Formation a submarine-fan deposit? The distributions of present-day orientations of paleocurrent markers from a substantial package of sediment (Fig. 10a) shows a unimodal distribution that is tightly clustered, but when estimated strain is removed a more dispersed distribution results (Fig. 10c). Both diagrams are plotted using both groove and flute measurements as "axial" data; directions 180° apart are not distinguished. The smaller number of flutes (Fig. 10b) indicates that the eastward mode of Figure 10a represents the true current direction. Figure 12 shows paleocurrent distributions from successive 100 m portions of the same section; major changes in mean current direction are obvious. These observations support a fan-like depositional system in which the sediment dispersal route or routes changed through time. We therefore interpret the Goldenville Formation as a submarine-fan deposit.

Modern submarine fans range from about 20km in length (e.g. Navy Fan; Normark and Piper, 1972) to more than 2000km (e.g. Bengal Fan; Curry and Moore, 1971). Numerous models have been

proposed as bases for the understanding of ancient submarine-fan deposits, but there is as yet no general agreement on the nomenclature or classification of submarine fan environments. Probably the most commonly used models are those of Walker and Mutti (1973) and Walker (1978), which are based primarily on interpretations of ancient fan deposits, and that Normark (1970, 1978) which is based exclusively on observations of modern fans. These models are shown in Figures 41 and 42.

Two basic types of depositional and physiographic features are identified in all fan models: *Channels* are elongated depressed areas within which sediment gravity flows are to some extent confined. Channels may be bounded by levees, and may be sinuous, or straight, or branching ('braided'). Depositional, depositional/erosional, and erosional channel types are recognized in modern examples (Nelson and Kulm, 1973). In contrast, *depositional* lobes, *suprafans*, and whole *fans* are convex-upward sediment bodies produced by unconfined or variably directed flows. In most models the larger lobe-like features (e.g. suprafans) have smaller-scale channels on their upper surfaces. However, Mutti (1977) suggested that lobes may form down-current from channel terminations, separated from them by a zone of sediment bypassing.

Channels and lobes are often identified in ancient vertical sequences on the basis of trends in bed thickness and grain size (Ricci-Lucchi, 1975). Thinning and fining-upwards megasequences are postulated to represent the filling and abandonment of channels, whereas prograding lobes are believed to produce thickening and coarsening upwards trends. However, such megasequences might also be produced by lateral migration of facies zones.

Major sandstone packages

Figures 4 to 7 show the distribution of major sand packages in the area studied on the south limb of the Sober Island Syncline. The following account is based mainly on well-exposed typical examples from magnetic unit E on Phoenix and Dipper Cove Island (Fig. 5) and from a complex of major sand packets in unit I and the base of unit J, which may be traced through Ironbound, Phoenix and Stoney islands eastward to Taylor Head and Salisbury Islands (Fig. 6).

Figure 5 shows lateral correlation of unit E between Tangier and Psyche Island, approximately 12km apart along strike. Three closely spaced sections were measured on Phoenix and adjacent islands, showing that unit E in this central area is a sandstone-dominated interval composed almost entirely of laminated to massive and internally scoured sandstones. The laterally equivalent sections on Tangier Island to the west and Psyche Island to the east contain a greater proportion of slate and graded sandstone, as well as many sandstone units of variable thickness. A greater number of separate depositional events appear to be recorded on the flanks of the sandstone body than in its centre. A pair of slate units can be identified on Tangier and Psyche islands but are absent in the centre of the package. These observations indicate that a number of erosion surfaces are present within the package, at which substantial parts of the section have been eroded in the central area. Indeed, the almost complete absence of slate from the central sections indicates that most flows must have been more erosive in this region than on the flanks of the sand body. The base of the package also shows erosional down-cutting into the underlying slaty sequence in the central area.

Figures 8 to 43 show a correlation of horizons within this package, based both on gradiometer peaks and lithological matching. A number of major erosional surfaces are identified but other erosion surfaces may be present in addition to those shown; bed-by-bed correlation is generally uncertain, due to the short-distance lateral facies changes in this unit.

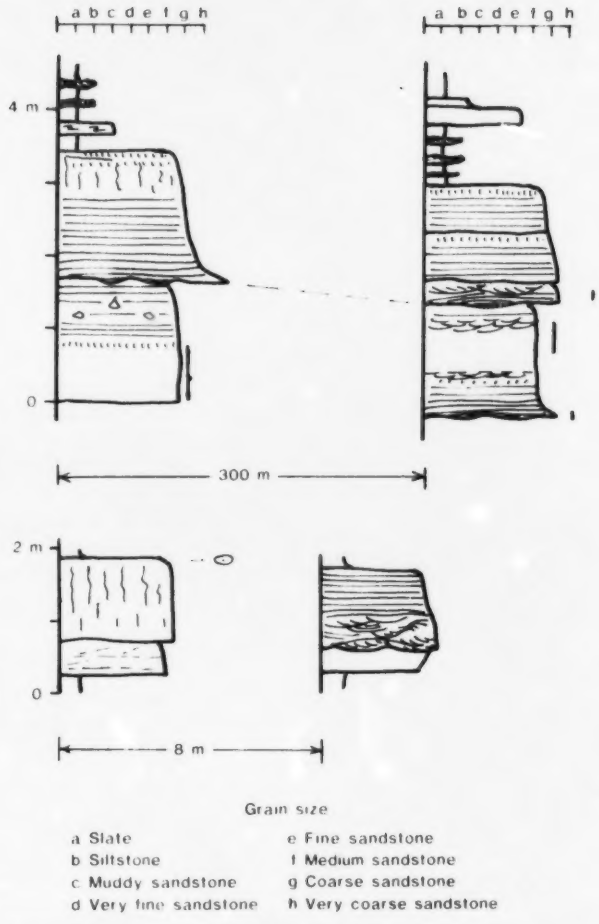


Figure 39a. Examples showing lateral variability of thick-bedded sandstones. Symbols and grain-size categories: see Figure 8.

Localization of sandstone deposition in the Phoenix Island area during unit E time was clearly due to channelization of flows. Repeated erosional events occurred in essentially the same place during deposition of a substantial thickness of sediment, suggesting that the channel was constrained between levees. This hypothesis is confirmed by paleocurrent data for the central and marginal areas. Grooves from the central sections have a mean pitch of 8°E, which after removal of strain and rotation to horizontal indicates a vector mean current azimuth of 047°. If this is taken to indicate the channel axis direction, then the Psyche Island section lies on the right bank of the channel (Fig. 44). Paleocurrents in this section yield a mean azimuth of 091°, indicating substantial divergence of flow from the axial region. The difference between the two vector means is highly significant according to the Watson Williams test described by Mardia (1972), and the sense of divergence is consistent with the inferred orientation of the channel (Fig. 44).

Other major sandstone packages show similar sedimentary facies and stratigraphic relationships. In addition, some contain intraclast conglomerate horizons, providing further evidence of erosional events (Fig. 9). A package exposed on Ironbound Island is in a position on-strike with magnetic unit I which is a distinctive negative feature on the vertical gradient profiles further east (Fig. 6). The

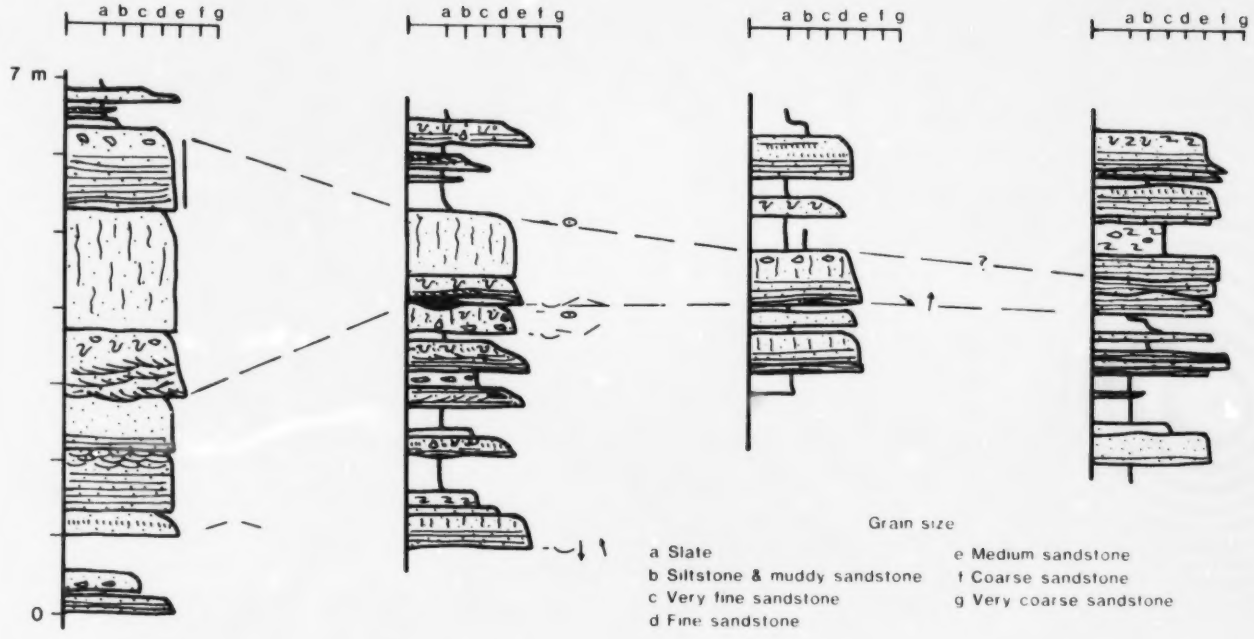


Figure 39b. Lateral variability of sand package with steeply pitching palaeocurrent. Location of columns from left to right: Tangier Island, Phoenix Island, Dipper Cove, Psyche Island. Symbols and grain-size categories: see Figure 8.

disappearance of this unit between Phoenix and Ironbound islands can be attributed to erosion of a channel which was subsequently filled by the major sandstone package. This channel must have been eroded to a depth of at least 40m (Fig. 6).

Within the major sandstone packages, internally scoured and laminated to massive sandstone beds are generally organized in thinning-upwards cycles, in some cases separated by major erosional events. These cycles probably represent progressive filling of channels, as suggested by Ricci-Lucchi (1975). Filling was generally followed by a new erosive event. Comparison of the thicknesses of equivalent portions of the central sections (Fig. 43) shows that the sandstone depocentre shifted during the history of the major sandstone package. The major packages should therefore be regarded as *channel complexes* rather than single channels; each represents a leveed belt within which a succession of channels was developed.

Figure 8 shows lateral variation at the base of the unit E major sand package and illustrates the facies differences between the channel complex axis and the inferred levee deposits on Psyche Island. The latter are thinner bedded and contain a greater proportion of slate. Sandstone of the inferred levees mostly fall into the laminated to massive and graded facies, with only rare internally scoured sandstone; however wavy laminations and lenticular beds are common. Many beds are laminated throughout suggesting that traction sedimentation was predominant on the levees; this presumably reflects the lower concentration of sediment in portions of the flow that escaped from the main channel. Muddy sandstones are also more common than in the axial regions, suggesting that unstable slopes were often built up in the levee environment, resulting in remobilization by slumping and debris flow.

The equivalent section on Tangier Island is intermediate in character between the 'axial' sections and that on Psyche Island. It also represents a channel margin or levee environment. The along-strike distance from Tangier Island to the axial region is 4.5 km. Using this as an estimate of the half-width of the sand package and assuming its axis pitches at 8° to the northeast, parallel to the mean groove orientation, the present true width of the sand package is calculated to be approximately 1.3km. This neglects the effects of layer-parallel shortening, which has narrowed the sand body. If the long axis of the strain ellipse on bedding surfaces is assumed to be a line of no finite strain, the original width of the channel complex before deformation can be calculated, using the same 2:1 strain ratio as that used to re-orient paleocurrent markers. The width obtained is 2.6km.

The presence of thin (5-30m) fining-upwards sequences in this package confirms the validity of such sequences as indicators of a channelized environment. The whole package shows a light thinning-upwards tendency in its axial region but the flanking sequences on Tangier and Psyche islands show an overrall thickening-upwards tendency. This may be due to the progressive escape of later flows from the axial region. Thus thickening-upwards trends do not necessarily identify progradational lobes, and should therefore be interpreted with caution.

Minor sandstone packages

Sections outside the major sandstone packages generally contain sandstone bodies from 5 to 20m in thickness, intercalated with thinner bedded sand and mud. These minor sandstone packages sometimes show either thinning-upwards or thickening-upwards megasequences.

Thinning-upwards packages exhibit the same characteristics as the smaller thinning-upwards units within major sandstone packages, and consist mainly of laminated to massive and internally scoured sandstones. They typically show thinning or interdigitation with slate when traced 5-10km along strike. Like their counterparts within the major packages, these are interpreted as channel fills, the

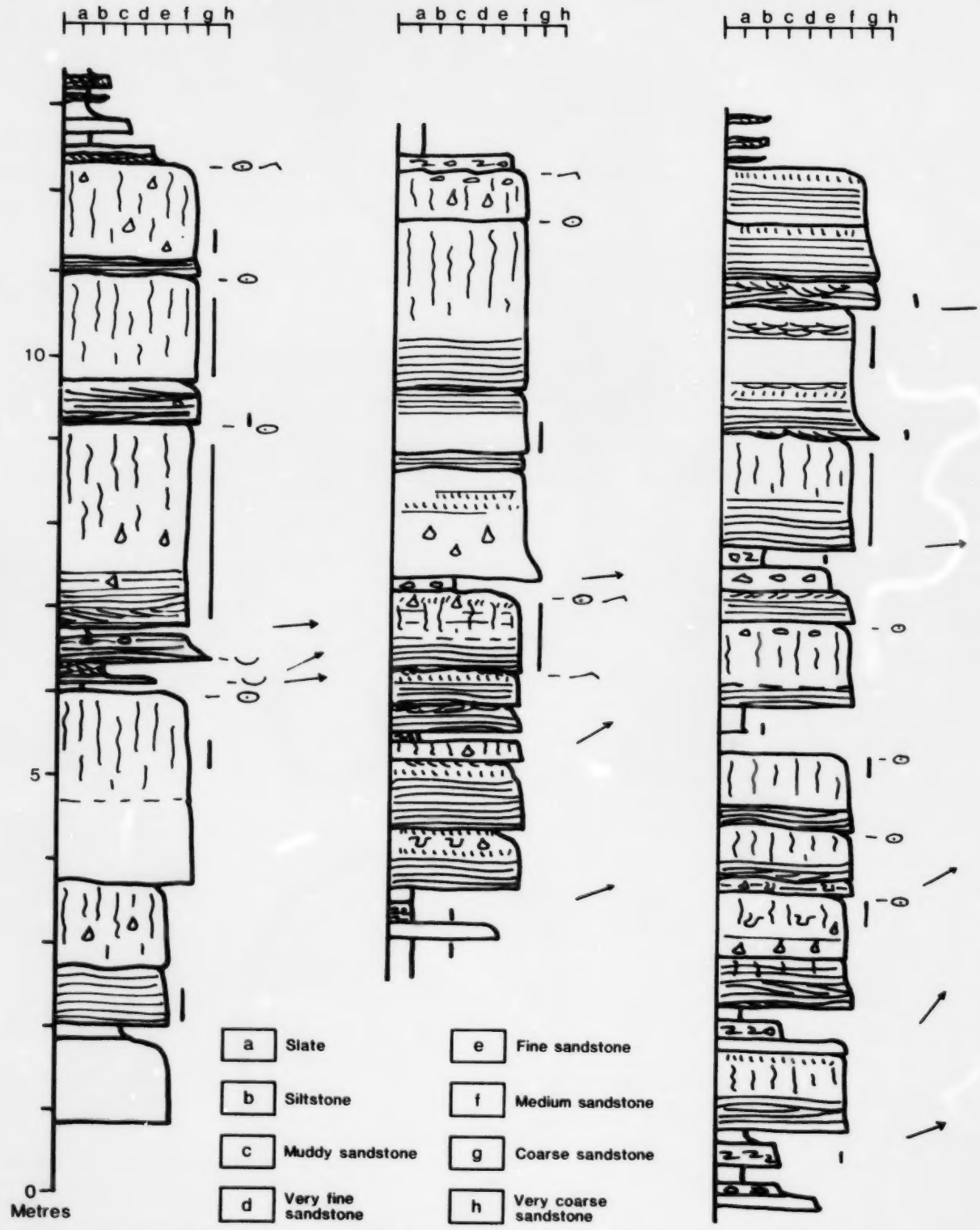


Figure 40. Sequences from south end of Phoenix Island (unit C) showing three thickening-upwards cycles. Symbols and grain-size categories: see Figure 8.

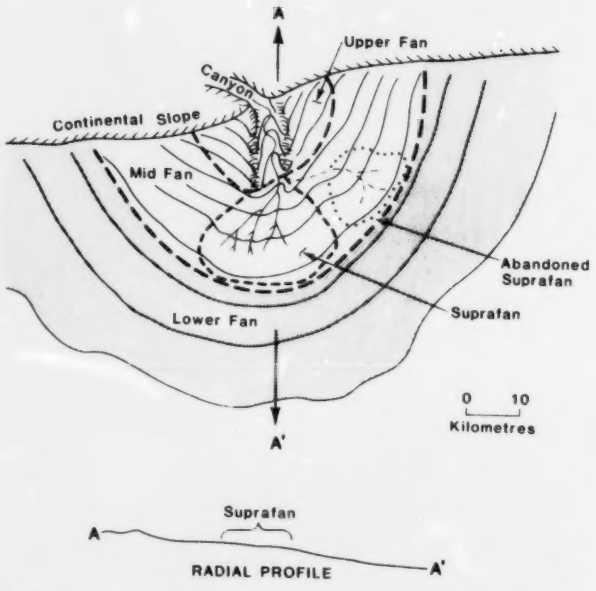


Figure 41. Normark (1973) model for a typical submarine fan.

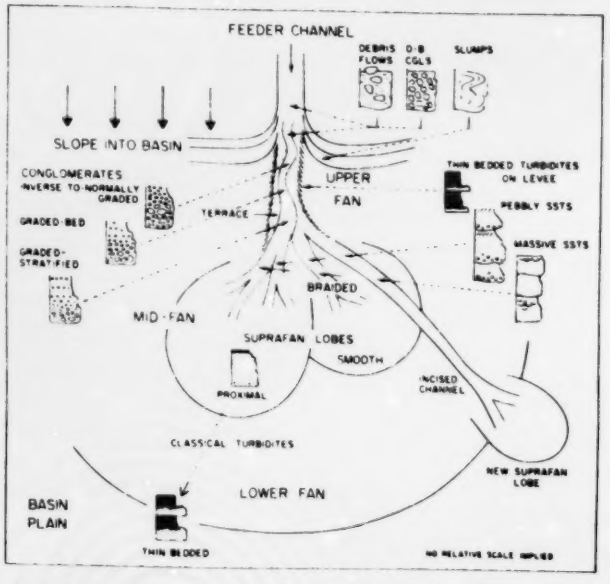


Figure 42. Submarine fan model of Walker (1978)

principal difference being that the minor packages represent channels that were abandoned, rather than rejuvenated, after a single fining-upwards cycle. This may have been because levees were smaller or nonexistent on these channels. There is insufficient paleocurrent data to deduce the orientation or width of most "minor" channels; their lateral continuity suggests their widths may be comparable to or even greater than those of the major sandstone packages.

Thickening and coarsening-upward minor sandstone packages are 6-12m thick. They are well seen at the south end of Phoenix Island (Fig. 40). Typical cycles have slate and muddy sandstone at the base, overlain by gradually thickening laminated to massive sandstone beds which pass up into internally scoured sandstone. Paleocurrent directions sometimes show a systematic change in orientations from bottom to top in a thickening-upwards sequence.

These thickening-upwards packages are comparable in thickness and bedding characteristics with examples described from other submarine fan deposits (e.g. Walker, 1978; Ghibaudo, 1980), and interpreted as depositional lobes. However, the examples described from these examples show more abundant Bouma sequences than the Goldenville thickening-upwards packages. Sand bodies representing suprafan lobes of the type described by Walker (1978) and Normark (1978) should be thicker than the channel sands developed in the same system, since according to these models, channels are built across the top of the lobes. Thickening-upwards packages in the Goldenville Formation are only the same thickness as the thinning-upwards sequences representing channels. They therefore probably represent rather small progradational features associated with the terminations or leveees of individual channels.

One larger scale thickening-upwards package is seen on Guildford Island (Fig. 4). This contains minor thinning-upwards packages at its top and is possibly a true suprafan lobe.

Slaty intervals

Intervals between sand packages are characterized by the presence of abundant (50 per cent or more) slate, thin graded sandstones, and muddy sandstones. The thicker slaty intervals can sometimes be traced across the whole area studied, but individual sand and silt layers show poor lateral continuity, even over distances of a few hundred metres. Paleocurrents from adjacent sand beds often show wide scatter in orientation (Fig. 8).

These muddy intervals cannot be classified as basin plain or outer fan turbidites, which would be expected to show good continuity of bedding and reasonably coherent current directions. They are probably outer levee and inter-channel sediments. Variable current directions resulted from spill-over from more than one channel, or from crevassing at several points on a single levee. Muddy sandstones with slump structures are found in most slaty intervals. They may reflect either a regional paleoslope or localized over-steepening of levees or channel margins.

Sedimentary environments

Figure 45 shows a schematic model which includes all the submarine fan elements identified in the part of the Goldenville Formation studied by us.

Major sandstone packages are represented by "channel complexes" equivalent to the fan valleys of Normark (1978). In the centre of the valley, a single channel is probably active at any one time, but shifts or migrations in the course of this "thalweg" occur periodically. Thalweg migration is limited, however, by the presence of substantial levees, which, on the basis of modern fan studies may be considerably wider than the valley itself. If the thickness of thinning-upwards cycles indicates channel depth, then the central channel is 10 to 30 m deep. The depth of the whole valley cannot be determined, because it is partially a constructive feature. In the one example of a valley cut by erosion (Ironbound Island), at least 40m of sediment (present thickness, after deformation and compaction) was removed. Channel sandstones are internally scoured and laminated to massive types, with occasional intraclast conglomerates formed by erosion during channel migration. The levees are characterized by laminated to massive and graded sandstones, probably passing out into cross-laminated siltstones, and by muddy sandstones produced by sediment remobilization on slopes.

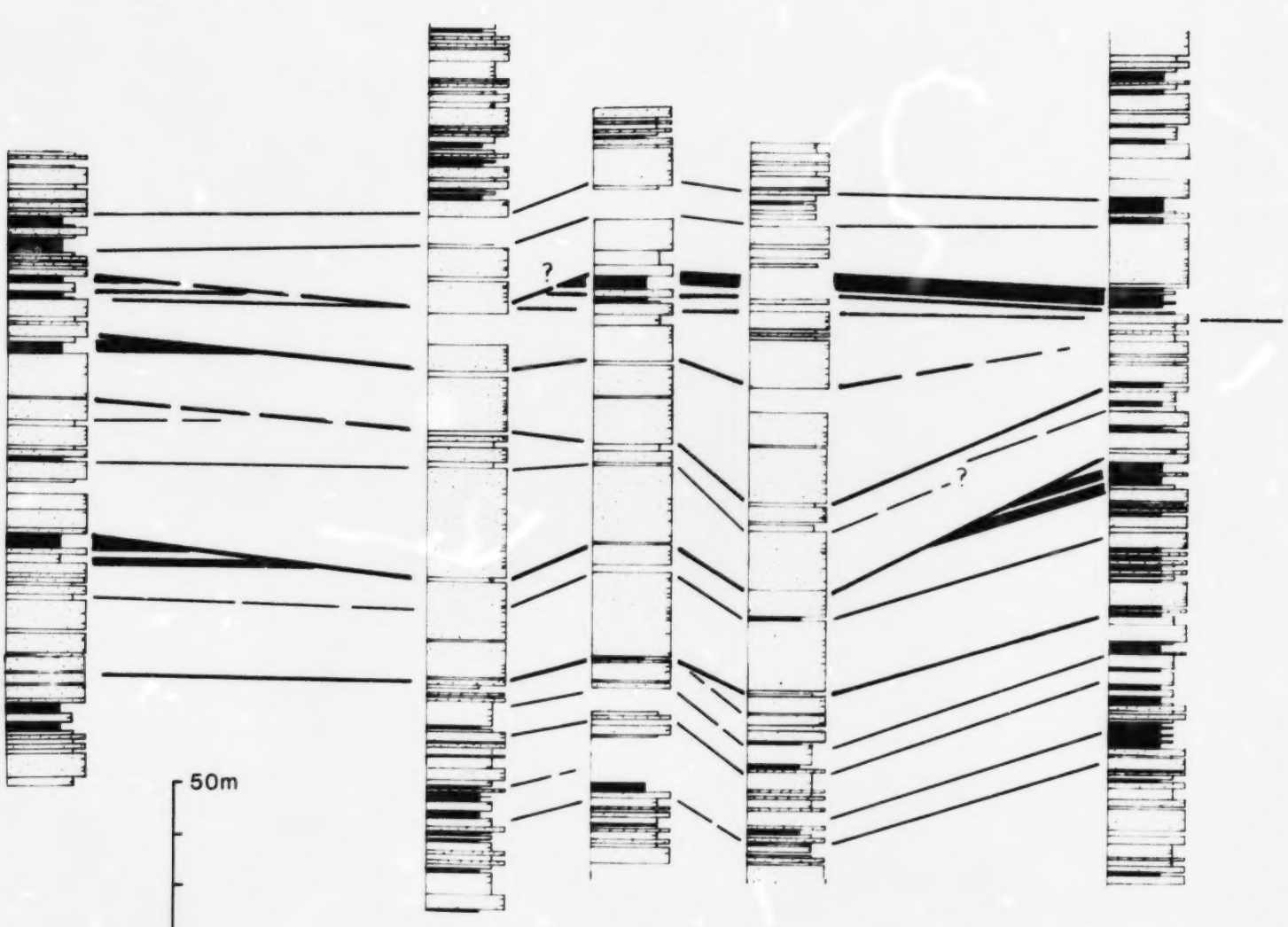


Figure 43. Diagram to show proposed correlation of sandstone packages in major sandstone package (Unit E). Location of columns from left to right: Tangier Island, Phoenix Island (west coast), Phoenix Island (east coast), Dipper Cove, Psyche Island.

Leveed fan valleys characterize "upper fan" environments according to Normark (1978); Walker's (1978) model (Fig. 42) predicts a variety of conglomeratic facies in this situation; clearly only finer sediment was supplied to the Goldenville fan. Major sandstone packages are common in the small area studied by us; we conclude that numerous leveed fan valleys existed in the Goldenville Formation at any one time. In this, it resembles large modern submarine fans (Bengal fan; Curry and Moore, 1971) rather than small continental borderland fans which generally have only one fan valley.

Sedimentary sequences between major sandstone packages include numerous minor sandstone packages, most of which are believed to be channel fills. These channels probably lacked levees, or if levees were present they were not sufficiently substantial to prevent frequent channel switching and abandonment. These sequences probably represent environments assigned to the Middle fan by Normark (1978). Large progradational features such as suprafans do not seem to have played a major role in the development of the Goldenville middle fan regions. Only one example of a major thickening upwards package — possibly a suprafan or depositional lobe — occurs in the sequence studied. Other thickening upwards

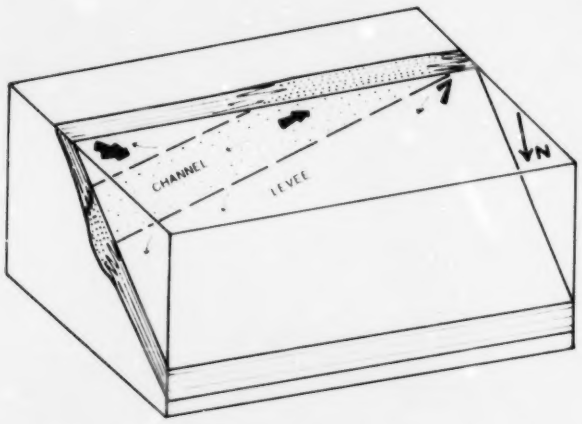


Figure 44. Schematic block diagram to show inferred relationships of paleocurrent directions with major sandstone package of unit E. Compare Figure 12.

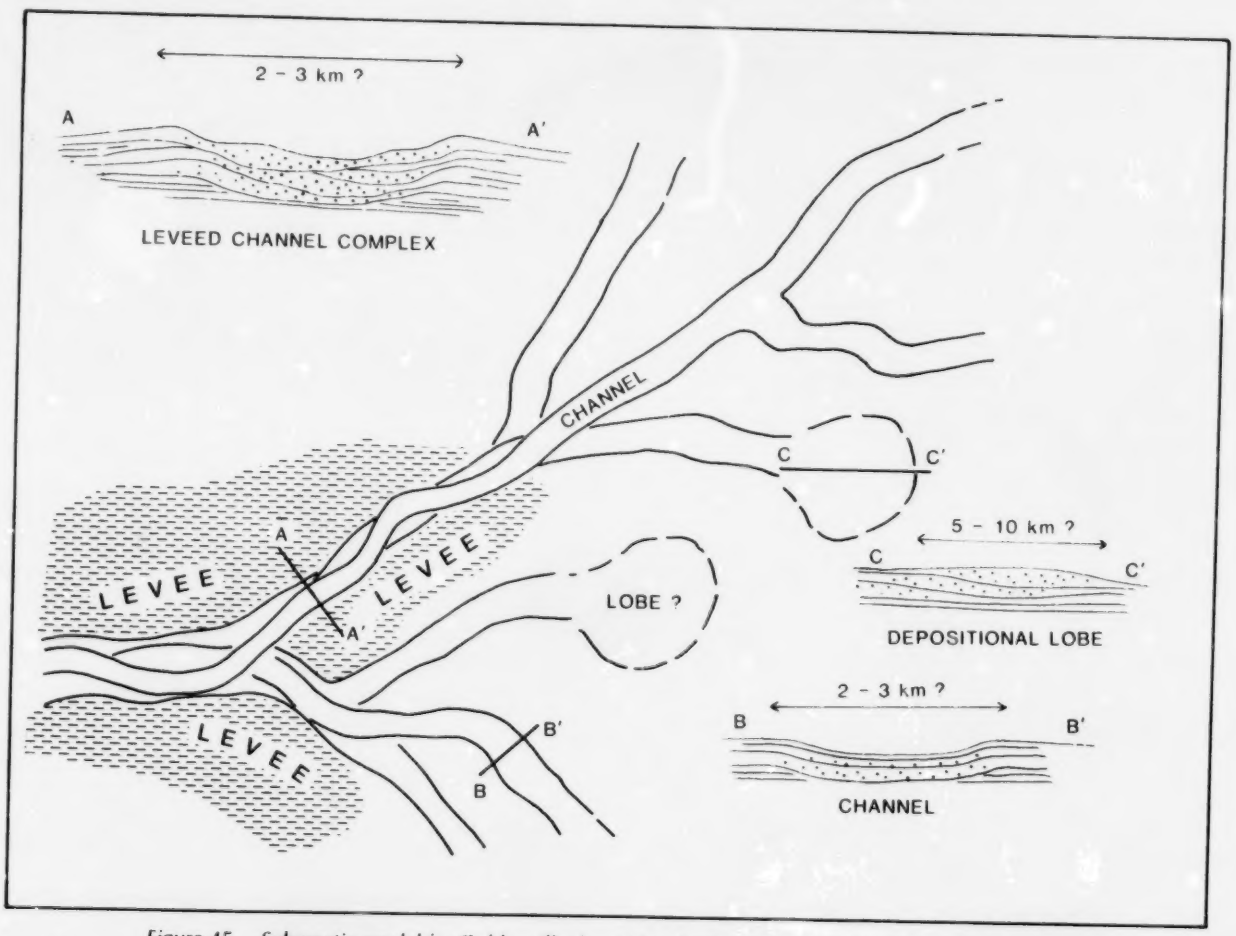


Figure 45. Schematic model for Goldenville depositional system, showing the main submarine fan elements present. Fan is dominated by channels and channel complexes. Evidence for depositional lobes is less clear; coarsening-upward packages may represent either lobes or channel margins which prograded. Configuration of diagram is loosely based on Astoria Fan of Nelson and Lulm (1973).

sequences are small and may have been little more than channel mouth-bars. Normark (1978) suggests that suprafan development may be controlled by the grain size distribution and rate of sediment supply to the fan; muddy fans develop extensive leveed channel systems and small suprafans. Although the Goldenville Formation is predominantly sandstone, it has few coarse sands and conglomerates and its sandstones have an abundance of muddy matrix; it may therefore have developed in the same way as modern mud-dominated fans.

ACKNOWLEDGMENTS

We wish to thank Dr. J.R. Henderson and Dr. W.H. Poole for their assistance in setting up the project and for much logistical help in the field. Edna Wilson, Fred Boner, Kevin Stevens and Lauryl Lefebvre assisted in the data collection. Joanne Staszko and Denise Turner assisted in the laboratory, and Elizabeth Balcom typed the draft manuscript. We are grateful to Audrey and Lindsay Beaver for the use of their house in Necum Teuch, and to Bob Blumsum, Barry Diamond and the staff of the Nova Scotia Department of Lands and Forests for their advice and assistance in Taylor Head Provincial Park. We acknowledge useful discussion with Jack Henderson, Duncan Keppie, Paul Smith, Brian O'Brien, Simon Haynes, Ron Pickerill, Tom Wright, Bob Ryan and David Piper.

This project was supported by the Geological Survey of Canada (D.S.S. Contract OST 83-00021) under the Canada-Nova Scotia Co-operative Mineral Program 1981-84. This report also includes some results of fieldwork in 1982 which was supported by the Nova Scotia Department of Mines and Energy.

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